Repositioning Forward-leaning-vehicle Occupants During Normal Driving and Harsh Braking

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Abstract A forward-leaning occupant posture reduces the distance to nearby structures (e.g., dashboard, steering wheel, or seat ahead), leading to non-optimal utilization of the available ride-down distance in the case of a frontal crash. This study examined whether forward-leaning occupants can be repositioned using reversible belt-tensioning during constant-speed travel at 70 km/h and controlled braking, and whether responses differ by belt system or sex. Sixteen volunteers experienced both conditions in upright (25°) and forward-leaning (−15°) postures using Belt-in-Seat (BIS) and B-post belt geometries. Reversible pre-tensioning (250 N or 500 N), triggered during constant speed or at braking onset, was used to reposition forward-leaning occupants, with upper-body kinematics and muscle activity recorded.

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Low-level pre-tensioning returned most volunteers to their preferred upright posture during constant-speed travel, though elevated muscle tension limited or delayed repositioning in some individuals. During braking, tested tension levels did not fully reposition the average volunteer.

Forward-leaning volunteers began with the upper torso positioned ~300 mm forward of upright. During constant-speed repositioning with the B-post belt, the upper torso returned to ~50 mm forward of preferred seating within 500 ms. The BIS geometry achieved near-complete repositioning, whereas simultaneous braking slowed the response and left the upper torso ~90 mm forward. No significant sex-based differences were observed. Flexor muscles were more active than extensors during repositioning, indicating resistance to the imposed movement.

This work provides a dataset on volunteer repositioning from forward-leaning postures at 70 km/h, including scenarios involving controlled braking, suitable for Human Body Model evaluation.

Keywords *Braking kinematics, Forward-leaning occupants, Repositioning, Reversible belt, Volunteers.*

I. INTRODUCTION

During the past decade, research attention has increasingly focused on occupant behaviour and posture prior to a crash, including actions such as braking and steering. In a study involving 75 front-seat passengers during regular car riding, passengers frequently adopted seating positions that differed from those used in standardised crash testing [1]. Among the observed postures was a forward-leaning posture , in which the passenger moved away from the seatback, occurring in almost 10% of the studied frames.

In a forward-leaning occupant postures the distance between the occupant and surrounding vehicle structures (e.g., dashboard, steering wheel, or seat ahead) is reduced, increasing the likelihood of direct head contact, thereby elevating head and neck injury risk [2]. This posture also alters kinematics, leading to earlier airbag interaction; in proximity, such out-of-position deployment can increase head and neck loading [2]. Additionally, seat-belt performance may be reduced, with suboptimal routing and increased loading on the clavicle and thorax. A forward-leaning posture results in a lack of contact with the seatback, which may increase lateral excursion in a lateral crash [3], as the occupant is no longer supported by the side bolsters. Because the forward-leaning posture can influence the kinematics and restraint interactions in a potential crash, several studies have examined methods to reposition the occupant from a forward-leaning to a more upright, nominal posture.

Repositioning efforts have been studied both in volunteer testing and in simulations. In a sled-based volunteer study, participants were repositioned using seat belt pre-tensioning and an acoustic warning [4-5]. Repositioning trials were conducted both with and without sled acceleration. The results showed that belt pre-tensioning was

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effective in returning occupants to an upright posture, with larger pre-tensioning forces producing greater effects. Acoustic warnings also induced repositioning but were less effective than mechanical pre-tensioning. Muscle activity analyses presented in [5] showed the highest activation in the sternocleidomastoid (SCM), (neck flexor), followed by the middle trapezius (shoulder adductor) and rectus femoris (hip flexor, knee extensor). In a simulation study, the SAFER Human Body Model (HBM) was repositioned using belt pre-tensioning [6]. Two belt configurations—a conventional B-post belt and a Belt-In-Seat (BIS) system—were evaluated across several pre-tensioning levels (200 – 600 N), with simulations performed both with and without braking acceleration. The model was successfully repositioned to an upright posture under all pre-tensioning conditions, with the BIS system demonstrating greater effectivenessthan the B-post configuration. The study also indicated that the HBM resisted repositioning via activating the neck and lumbar flexor muscles.

Previous volunteer studies have reported mixed findings regarding sex-based differences in occupant response. Some studies found similar displacement patterns for males and females during braking or frontal crashes [7-9], and during low acceleration frontal crashes [10]. However, differences were observed in other studies [11], including higher acceleration frontal crashes in [10] and in certain lateral and oblique manoeuvres [9]. In contrast, when volunteers were repositioned from a forward-leaning to an upright posture, no sex related differences were found [4].

Because no volunteer studies have investigated repositioning from a forward-leaning posture in a realistic in-vehicle setting during actual road driving, the effectiveness of belt pre-tensioning for occupant repositioning in a true vehicle environment remains unclear.

Furthermore, existing studies on repositioning from a forward-leaning posture have been limited to measurements of the trapezius, sternocleidomastoid, and rectus femoris muscles. It therefore remains to be determined whether the resulting muscle activation patterns involve extensor muscles, potentially facilitating repositioning, flexor muscles, potentially resisting repositioning, or only minimal overall muscle activation.

Additionally, while previous volunteer studies have reported mixed findings regarding sex-based differences in occupant response to pre-crash interventions it remains to study if there exist sex difference in muscle activation or if the source of any sex difference is from size differences.

The primary aim of this study was to investigate the repositioning of volunteers from a forward-leaning posture in a vehicle environment. The volunteer experiments were designed both to improve understanding of occupant responses, during repositioning at constant velocity and controlled braking, and to provide tuning and validation data for active HBMs.

II. METHODS

Sixteen volunteers were exposed to either controlled braking or no-braking conditions while seated in upright or forward-leaning postures (Fig. 1) in a car driven on a test track. The initial torso angle in the upright posture was 25°, whereas in the forward-leaning posture it was approximately −15°. Seat belts equipped with reversible pre-tensioners were used both to reposition forward-leaning occupants and for those seated upright. Volunteers were tested using a custom-made BIS geometry, with a traditional B-post belt configuration serving as the reference condition. Tests were performed on a closed test track with no other traffic present, using only straight, flat road sections. The study protocol was reviewed and approved by the Swedish Ethical Review Authority (Etikprövningsmyndigheten; Application No. 2022-03970-01).

Fig. 1. Upright (left) and forward-leaning (middle) volunteer in the test-vehicle seat, and BIS installation (right).

Research Questions

The following specific research questions were analysed to meet the aims of this study:

Q1. Should analyses be performed separately for male and female participants?
Q2. Can a forward-leaning occupant be repositioned using belt pre-tensioning?
Q3. What magnitude of belt force is required to reposition a forward-leaning occupant?
Q4. Does belt geometry influence the ability to reposition a forward-leaning occupant?
Q5. Which muscles are activated during repositioning from a forward-leaning posture?
Q6. Does the repositioning intervention affect pelvis angle?
Q7. What is the repositioned occupant posture compared to an upright occupant, and what if no repositioning occurs?
Q8. Do occupants respond differently to braking depending on their initial posture?
Q9. Does belt geometry influence occupant response when seated in an upright posture?
Q10. What is the effect of belt pre-tensioning when the occupant is in an upright posture?

Test Events

Each volunteer was subjected to a total of 21 test conditions, consisting of forward-leaning, upright and reclined initial postures. Selected conditions were replicated, whereas others were repeated due to experimental constraints, resulting in approximately 28 tests per participant conducted within a total duration of about 60 minutes (see Table E 5). This study focuses on tests in which volunteers were repositioned from a forward-leaning posture (Fig. 1) via belt activation and compares these results with reference events performed in an upright posture (Table 1).

The test conditions varied with respect to initial torso angle, presence or absence of braking, belt-system configuration—Standard Belt (SB) or Pre-Tensioned (PT)—and PT force level (low: 250 N; high: 500 N). Events H and J were systematically repeated twice.

A test event began when the experiment leader—who also served as the driver—activated the measurement system, selected the test settings on the control panel, and pressed the trigger. The trigger signal then initiated the brake robot, the belt pretensioner, or both, depending on the test configuration.

Volunteers were instructed to place their feet on the provided support, rest their hands in their lap, and remain relaxed throughout the tests. Prior to the leaning-forward tests, the volunteers were asked to lightly lean their foreheads against a foam board that was resting on the floor in front of the seat (see schematics of initial position in Appendix G and initial belt angles for the various events in Appendix H). Prior to the upright seated tests, the volunteers were asked to look forward.

TABLE 1.
TEST EVENTS

Test Event	Torso angle (deg)	Braking on/off	Belt geometry	Belt	Pre-tension Level
B	-15	On	BIS	PT	High
C	-15	On	B-post	SB	-
D	-15	On	B-post	PT	High
E	-15	Off	BIS	PT	High
F	-15	Off	B-post	PT	High
G	-15	Off	B-post	PT	Low
H	25	On	BIS	PT	Low
I	25	On	B-post	PT	High
J	25	On	B-post	SB	-

Test Vehicle

The test vehicle was a large all-wheel drive Sports Utility Vehicle with leather seats and equipped with non-studded winter tires in good condition. The passenger seat was set to its lowest and most rearward position, lumbar bladders were deflated, and individualised foot support was provided using stiff foam boards placed in the footwell.

Two belt systems were installed: a traditional B-post belt and a BIS system. The B-post belt used the cars´

highest D - ring position, while the BIS incorporated a modified retractor mounted laterally on the seatback (Fig. 1). Both systems operated either as conventional inertia-reel belts or in PT mode. In SB mode, the B-post retractor locked automatically during braking and the BIS retractor was manually locked. In pre-tensioned mode, a separate 12 V power supply and an Arduino-controlled trigger system activated the belt to reach either 250 N (low PT level) or 500 N (high PT level) retractor force, with a webbing pull velocity of ~750 mm/s.

Braking was performed using a brake robot to ensure high repeatability. An electric motor applied brake-pedal force based on real-time vehicle deceleration until the vehicle came to a full stop. The brake robot was powered by two 12 V batteries connected in series and triggered using a separate Arduino circuit. In combined tests, braking was initiated ~50 ms prior to belt pre-tensioning to partially compensate for performance differences between the brake robot and the pre-tensioning systems. Specifically, the time required to reach steady-state vehicle deceleration and belt spool velocity.

Volunteers

Sixteen adult volunteers (nine males and seven females) participated in the study with anthropometric measurements provided in Appendix A, Table A 1. All participants reported no cervical or lumbar pain that could increase injury risk or influence test outcomes. Volunteers wore black cotton pants and a long-sleeve black cotton shirt, with openings allowing film targets to be attached directly to the skin.

Instrumentation

A Dewesoft measurement system (Dewesoft d.o.o.) was installed in the test vehicle. The setup included an Inertial Measurement Unit (IMU) (DS-IMU2), analogue sensors, two cameras (DS-CAM-GIGE-600c) connected to a camera communication module (CAM-BOX3), and a power unit (DS-BP4i) connected to a measurement computer (SIRIUSi STG).

a. The IMU was rigidly mounted to the vehicle chassis ~0.5 m behind the volunteer at seat cushion height.
b. Two cameras recorded upper body (2048 × 1088 pixels) and knee kinematics (1200 × 800 pixels): a side-view camera mounted on the driver-side window with its image plane aligned to the vehicle mid-plane, and a top-view camera mounted on the windscreen above the passenger's knees with its image plane parallel to the horizontal plane. Both cameras were equipped with 6.5 mm lenses. Two film targets were mounted on the Frankfort plane of the head (10 mm and 60 mm anterior of the external auditory canal, respectively), upper left corner of sternum, C7–T7 vertebrae, and anterior to right and left patellae.
c. Analogue sensors measured belt data and pelvis rotation. Diagonal and lap-belt forces were measured using two transducers (EL20-S458-A2-B; TE Connectivity, Netherlands) mounted on the right side of the belt segments and used for both B-post and BIS configurations. Belt payout was measured using two optical belt-movement sensors (LG200E) installed at the B-post and BIS spool attachment points. A skin-mounted gyro (RG-ARS 1075; Diversified Technical Systems, CA, USA), shaped to allow motion relative to the seatback, was attached near the sacrum (S1–S2) using double-sided tape.
d. Surface electromyography (EMG) was recorded bilaterally from four muscles: SCM, cervical paravertebral muscles (CPVM), rectus abdominis (RA), and lumbar paravertebral muscles (LPVM) (Fig. B 1) with a Grael unit (Compumedics, Abbotsford, Australia) during testing and in maximum voluntary isometric contractions (MVICs). Additional information on EMG data collection in Appendix B.

Video, analogue, EMG, and IMU data were recorded in 5 s triggered sequences (1 s pre-trigger, 4 s post-trigger). Analogue signals were sampled at 10,000 Hz, IMU data at 200 Hz, EMG signals at 2048 Hz, and video at 50 fps.

Data Processing

All analyses were performed in MATLAB R2022a or later (MathWorks, Natick, MA, USA). Data are expressed in a vehicle-fixed coordinate system with positive X forward and positive Z downward.

All instrument signals were filtered using a 3^{rd}-order Butterworth low-pass filter with a 10 Hz cutoff. Vehicle accelerations and rotational velocities, belt pay-out, and belt forces were zeroed using the mean of the first 0.2 s of data. Pelvis rotational velocity was integrated using cumulative trapezoidal integration to obtain pelvis position relative to the initial position, and the integrated signal was subsequently low-pass filtered.

To present all data using a uniform time zero, either the derivate of the longitudinal vehicle accelerations or the belt pull-in was used to define time zero (t_0) (a threshold value was used, such that the steep part of the vehicle acceleration or the belt position was aligned). The latter for tests with forward-leaning volunteers and active belts.

EMG onset time was calculated following [13]. The baseline phase was extended from the beginning of the trigger window to 0.5 s before t_0. Mean and standard deviation (SD) of baseline EMG were computed for this interval. A 50 ms moving average was applied to the EMG signals, and onset time was defined as the first instance after t0 at which the moving average exceeded the baseline mean + 2.5 SD.

EMG signals were filtered with a 4th-order Butterworth band-pass filter (10–500 Hz) [7][12-14]. Lumbar EMG signals affected by electro cardiac contamination were corrected using the Filtered Template Subtraction (FTS) method [15], leaving only minimal residual interference. Signals were rectified using a moving Root Mean Square (RMS) filter (20 ms window; [14]).

Recordings containing artifacts (e.g., motion artifacts or poor electrode contact) were excluded. EMG data were removed if any of the following criteria were met:

- Mean EMG in the interval 1.0–0.5 s before t_0 exceeded 0.5 MVIC.
- Peak EMG exceeded 2 MVIC.
- A single recording altered the mean activity for the full duration by more than 25%.

Video recordings from both cameras were digitised using TEMA Automotive (Image Systems AB, Linköping, Sweden). To compensate for image distortion, lens calibration and correction were performed in TEMA Automotive according to the provided protocol. Motion planes were subsequently defined at the occupants' mid-sagittal planes. Offset compensation was applied to markers located outside this plane (head, sternum, and seat-mounted markers). The sensitivity of the side-view camera to acceleration loading was found to be minimal.

Digitised video data were used to estimate head CoG and T1 displacements using data provided in Appendix D. Head-relative-to-T1 x-displacements were expressed in a coordinate system that translated and rotated with T1. For each volunteer tested in the forward-leaning posture, displacement data were offset by subtracting the individual's average position from Events H, I, and J (upright-posture tests) over the 1.0 – 0 s interval before t_0. This procedure yielded displacement measures representing each volunteer's position in the vehicle relative to their preferred upright posture. Pelvis displacement data were consistently zeroed at t_0.

In all figures, individual signals are shown as thin desaturated lines, the mean as a thick line, and shaded areas represent mean ± 1 SD.

To answer specific research questions the responses were reduced to single discrete values to enable comparisons across conditions (see Appendix D). Depending on the research question, one to two conditions were compared. Statistical analyses were performed using one-way ANOVA with a significance level of $\alpha = 0.05$.

Sex-specific analyses were conducted when evaluating potential male–female differences; otherwise, data from all participants were combined.

Outcome measures included upper body kinematics, pelvis rotation, EMG activity, and belt-system variables. These metrics were used to assess occupant repositioning, braking responses, and muscle activation during belt pre-tensioning repositioning.

III. RESULTS

In this study the resulting initial vehicle speed was 67 ± 2 km/h, with peak and steady-state decelerations of 9.3 ± 0.9 m/s² and 7.8 ± 0.7 m/s², respectively (Appendix C, Fig. C 1). Steady-state braking produced a vehicle pitch of 1.5° ± 0.3°. Volunteers were generally successfully repositioned from a forward-leaning posture by activation of the pre-tensioned belt when under steady-state vehicle conditions (Fig. E 6). The belt pay-in rate appeared constant until either the maximum belt load (500 N) or the programmed maximum pay-in duration was reached (Fig. E **7**). Final belt pay-in typically measured ~250 mm for the B-post belt and ~350 mm for the BIS belt (Fig. E 11). For some volunteers, the final increase in belt load was associated with torso contact against seatback, whereas for others it was likely due to belt straightening or muscle activation resisting the repositioning (Fig. E 11). When repositioning was attempted during braking, the overall response pattern was similar to that observed under steady-state conditions, but the total belt pay-in was reduced by ~70 mm for both belt geometries tested (Fig. E 13).

Q1 - Should analyses be performed separately for male and female participants?

Comparisons between male and female EMG activities are available in Fig. E 2 and Fig. E 4 and kinematics in Fig. E 1 and Fig. E 3. The analysis of significant differences between male and female responses, are presented in

Table E 1, Table E 2, Table E 3 and Table E 4. The analysis provided mainly insignificant sex-related EMG differences and kinematics. However, repositioning forward-leaning occupants resulted mainly in insignificant sex -related differences in EMG but significant sex-related differences in kinematics in some of the events (D, F and G,Table E 1) despite insignificant sex-related differences in belt pay-in (Table E 3). While the analysed kinematics included variabilities in both initial position in relation to preferred position and response to any belt pre-tension and any vehicle acceleration, **Error! Reference source not found.** provide a separate analysis of the responses to any belt pre-tension and any vehicle acceleration. This additional analysis also provided significant sex-related differences in kinematics between males and females for the events D, F and G.

Similarly, the analysis of male and female data during SB use (Events C and J), revealed mixed results. In event J males exhibited significantly greater displacements than females (Table E 1), while muscle activities were similar (Table E 2). Belt pay-in were also similar between males and females while belt loads were higher for males than females in event G, H and J (Table E 3).

Q2 - Can a forward-leaning occupant be repositioned using belt pre-tensioning?

Before the start of the Event F and G, volunteers leaned forward such that the upper torso (T1) was positioned ~300 mm anterior, 35 mm inferior, and flexed 40° relative to their preferred upright posture (Fig. 2, Fig. E 6, Table G 1). During constant vehicle speed, volunteers were repositioned by the B-post mounted PT belt, activated for 600–700 ms at low level and 500–600 ms at high level. The combination of significantly lower belt force (Table F 3) and longer activation duration at low PT, together with any prolonged muscle activation, resulted in significantly reduced upper torso horizontal displacement toward the upright posture compared to high-level PT (Table F 1). The upper torso moved to a position 80 mm (low PT) and 50 mm (high PT) anterior relative to their preferred posture within 700 ms (low PT) and 600 ms (high PT). The torso simultaneously rotated rearward, reaching an average angle of 12° across PT levels. The head was initially positioned 75 mm forward of relative to its preferred T1 location, with head protraction briefly increasing to ~90 mm (independent PT level, Fig. E 6). The neck began at ~30° of flexion and decreased to ~10° by 1 s into the Event G (Fig. 2) while decrease somewhat less for high PT (Event F).

When braking occurred simultaneously with BIS belt activation, repositioning was slower and resulted in a significantly more forward final posture (Fig. 3, Table F 1). During braking but after belt retraction, the upper torso remained 90 mm forward and 12° flexed—approximately 85 mm forward compared with the same belt configuration without braking (Fig. 3).

In general, a PT belt system can reposition a forward-leaning occupant. Braking reduced the amount of repositioning.

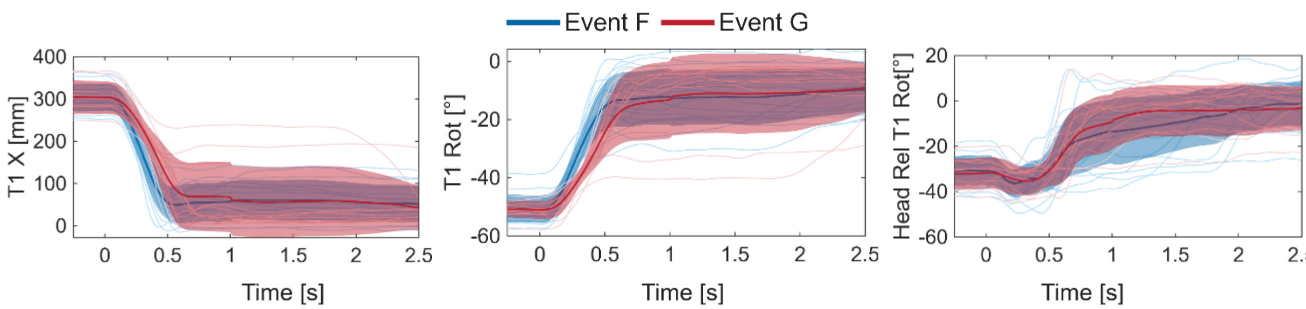

Fig. 2. Displacements for volunteers in forward-leaning posture when repositioned by PT belts. High PT level (Event F, blue) vs Low PT level (Event G, red). B-post belt geometry and constant vehicle speed. All data compared to preferred upright posture.

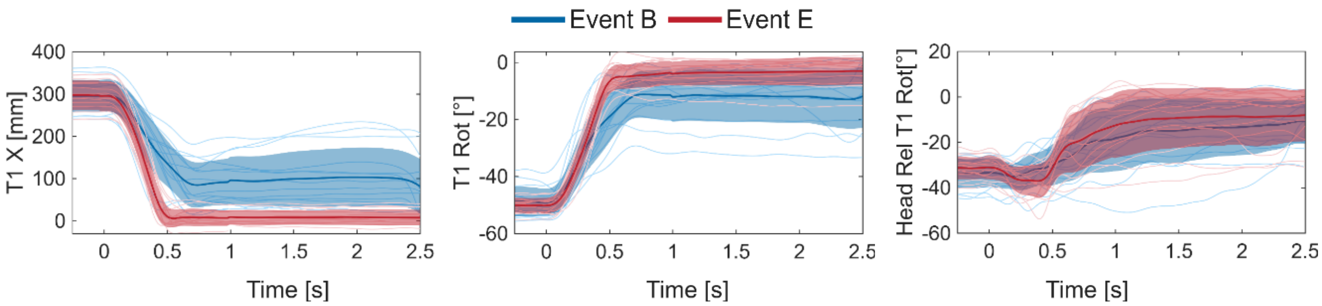

Fig. 3. Displacements for volunteers in forward-leaning posture when repositioned by PT belts. Braking (Event B, blue) vs Constant vehicle speed (Event E, red). BIS belt geometry and high PT level.

Q3 - What magnitude of belt force is required to reposition a forward-leaning occupant during normal driving?

In Event F, application of the high-PT level with the B-post geometry at constant vehicle speed generated maximum average diagonal-belt loads of 460 N and 250 mm of belt pay-in (Fig. 4), resulting in 250 mm of rearward upper-torso motion (Fig. 2). Under the low-PT condition, the maximum diagonal-belt load, belt pay-in, and rearward torso motion decreased to 225 N, 210 mm, and 220 mm, respectively (Fig. 4, Fig. 2). When braking was introduced (Event B), the belt-load rise time shortened, and the load remained elevated after torso repositioning was complete. In contrast, belt pay-in was substantially reduced, dropping from 340 mm to 270 mm when high-PT level with the B-post geometry was used (Fig. E 9) and rearward torso motion decreased to 215 mm (Fig. 3). In conclusion, a belt force magnitude of 225 N is sufficient to reposition several of the forward-leaning occupants during normal driving while during braking anterior relative a belt force of more than 460 N is required.

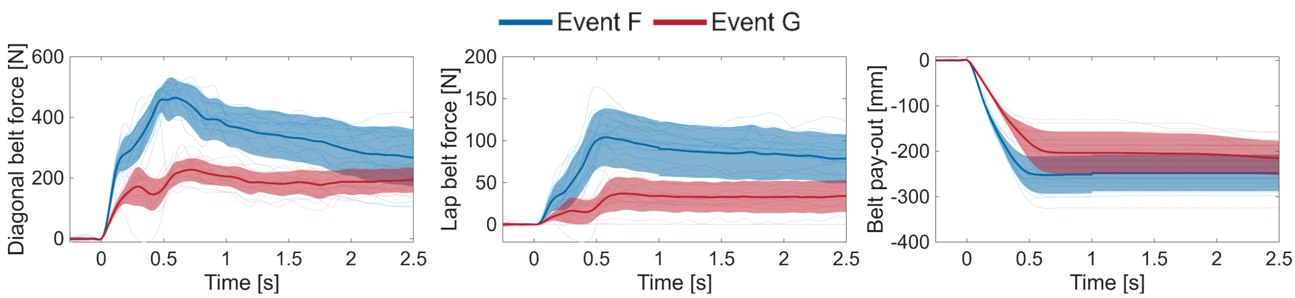

Fig. 4. Diagonal and lap belt force and pay-out (negative = pay-ins) for volunteers in forward-leaning posture when repositioned by PT belts. High PT level (Event F, blue) vs Low PT level (Event G, red). B-post belt geometry and constant vehicle speed.

Q4 - Does belt geometry influence the ability to reposition a forward-leaning occupant?

The initial volunteer posture was nearly identical for both the B-post and BIS geometries (Event E vs Event F, Fig. E 10). The volunteers exhibited similar repositioning behaviour for the first 400 ms with both the B-post and BIS geometries (Fig. 5 and Fig. E 10). After this point, the BIS configuration achieved more effective and complete repositioning.

Although differences in repositioning between belt geometries were not statistically significant (Table F 1), the final average upper-torso (T1) position for the BIS configuration was only 5 mm anterior and 3° more flexed relative to the preferred posture (Fig. 5), compare with 40 mm anterior displacement and 14° flexion for the B-post geometry (Fig. 5).

A likely explanation is that the B-post belt path was straighter than that of the BIS, resulting in a significantly faster rise in belt force and significantly reduced belt pay-in for the B-post system (Fig. E 11, Table F 3) and thereby providing for lesser repositioning than the BIS belt provided.

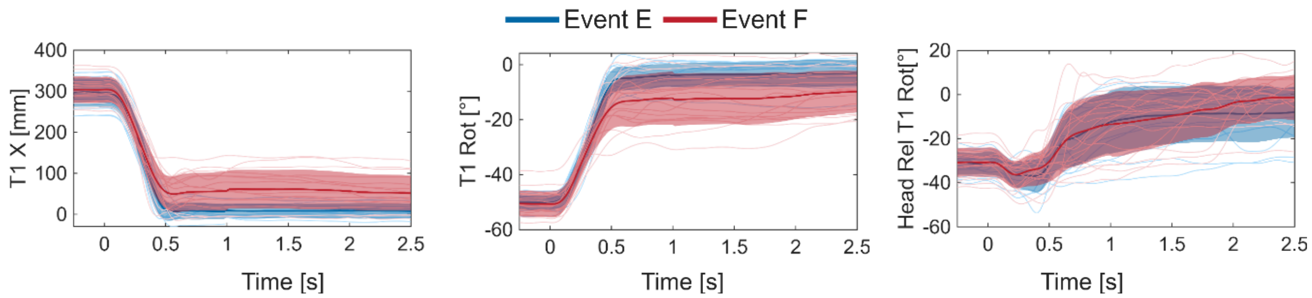

Fig. 5. Displacements for volunteers in forward-leaning posture when repositioned by PT belts. BIS belt geometry (Event E, blue) vs B-post belt geometry (Event F, red). High PT level and constant vehicle speed.

A pronounced difference in repositioning behaviour between the B-post and BIS geometries emerged when braking was added (Fig. 6 and Fig. E 12). Under braking, the BIS configuration moved the upper torso ~210 mm rearward, whereas the B-post configuration achieved only ~140 mm. There was a significant difference in head and upper torso rearward repositioning for the first second (Table F 1) despite insignificant differences in muscle activities (Table F 2). As in the no-braking condition, the B-post belt pay-in was limited by a combination of torso inertia and its straighter path compared to the BIS belt—although in this case to an even greater extent—and the lap-belt forces were correspondingly higher (Fig. E 13, Table F 3).

In summary, the BIS belt geometry provided greater occupant repositioning than the B-post geometry, with the differences becoming more pronounced when braking was applied.

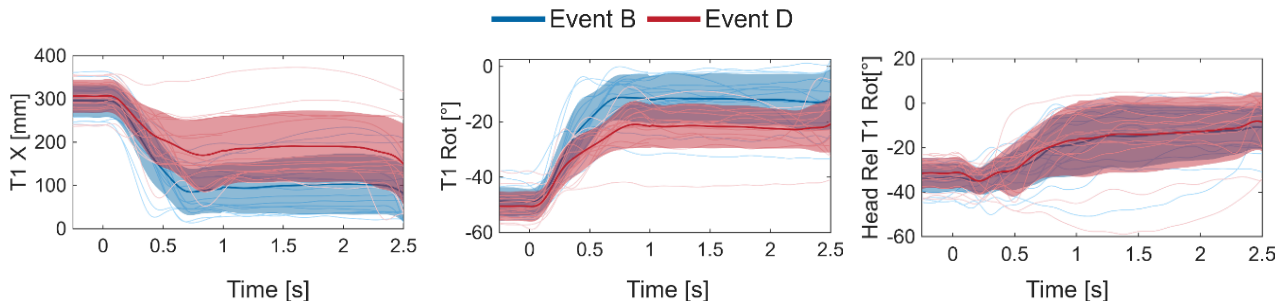

Fig. 6. Displacements for volunteers in forward-leaning posture when repositioned by PT belts. BIS belt geometry (Event B, blue) vs B-post belt geometry (Event D, red). High PT level and braking.

Q5 - Which muscles are activated during repositioning from a forward-leaning posture?

In Event E, where volunteers were exposed only to high-level BIS belt loading, the SCM muscles reached ~15% MVIC at around 140 ms after belt activation (Fig. E 2), while activation of other recorded muscles remained much lower. However, the RA muscle activations were sufficient to somewhat raise the legs in some of the tests.

When belt loading was combined with braking (Event D), SCM activation increased modestly to ~20% MVIC (Fig. E 24). Notably, a high PT belt activation combined with braking for leaning forward occupants (Event D) provided for earlier muscle activations, across all measured muscles, compared to SB for the same posture (Event C) and compared to conditions in upright posture (Event I, Fig. E 24).

Across several comparisons, muscle activation levels did not differ significantly—for example, braking versus constant vehicle speed with BIS activation (Events B vs E), or BIS versus B-post configurations (Events H vs I and Events E vs F) (Table F 2). In contrast, B-post belt activation at low and high level produced significant EMG differences in the SCM on both sides (Events F vs G, Table F 2).

Q6 - Does the repositioning intervention affect pelvis angle?

BIS belt pre-tensioning rotated the pelvis rearward by 8–12° for a volunteer initially leaning forward, with the significantly smaller rotation occurring when PT activation coincided with braking (Event B) and the larger rotation when PT was applied without braking (Event E) (Fig. 7, Table F 1). For comparison, during braking with a traditional belt (Event J), the pelvis rotated forward by ~12° (Fig. 7).

The BIS belt activation (Event B) provided ~5° significantly greater pelvis rearward rotations than the B-post belt (Event D) when braking was applied simultaneously for leaning forward volunteers (Fig. 7, Table F 1). Similarly, the BIS belt activation (Event H) provided ~4° less forward rotation than the B-post belt (Event I) when braking was applied simultaneously for upright volunteers (Fig. 7). Difference for the first 1 s was significant. The latter was ~8°less than when there was no belt activation (Event J) (Fig. 7). Belt activation at high level (Event F) provided similar average pelvis rearward rotation as the activation at low level (Event G) (Fig. 7, Table F 1).

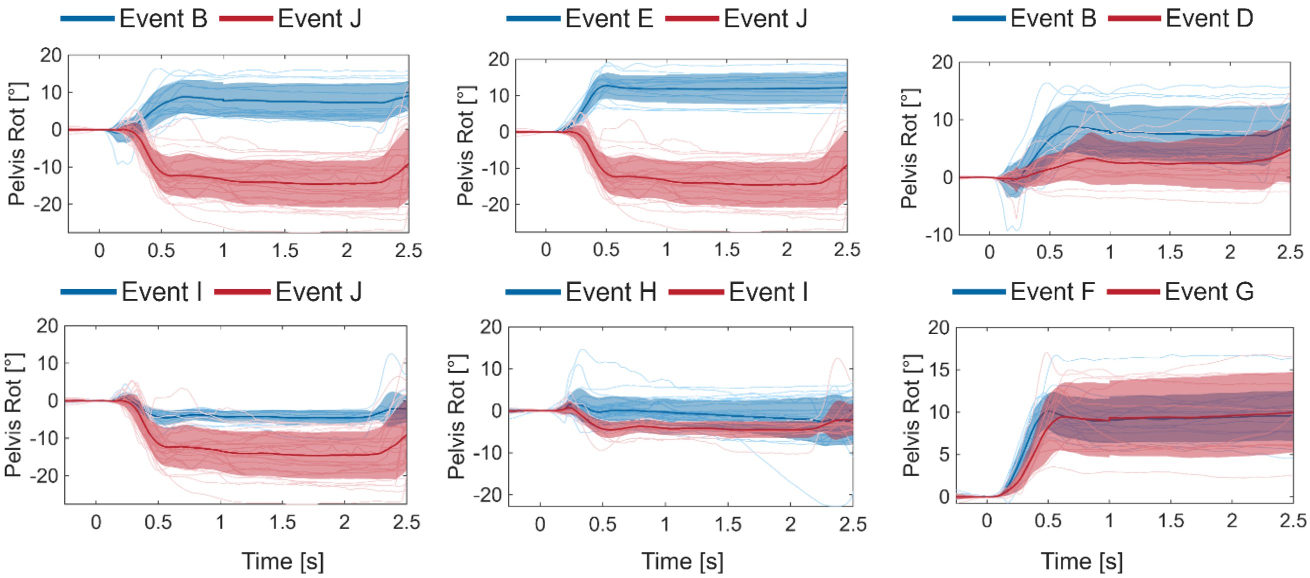

Fig. 7. Pelvis angular change as a function of time. Top left: Repositioned by BIS belt during braking (Event B, blue) vs SB and upright posture (Event J, red). Top middle: Repositioned by BIS belt at constant vehicle speed (Event E, blue) vs SB and upright posture (Event J, red). Top right: Repositioned by belt during braking; BIS (Event B, blue) vs B-post (Event D, red). Bottom left: Upright posture and exposed to braking; PT (Event I, blue) vs SB (Event J, red). Bottom middle: Upright posture and braking; BIS (Event H, blue) vs B-post (Event I, red). Bottom right: Repositioned by B-post belts. High PT level (Event F, blue) vs Low PT level (Event G, red).

Additional information on occupant kinematics and belt loads can be found in Appendix E (Fig. E 6 - E 7 and Fig. E 12 - E 21) where supplementary figures and tables provide detailed motion traces, belt-force profiles, and event-specific comparisons.

Q7 - What is the repositioned occupant posture compared to an upright occupant, and what if no repositioning occurs?

Upper-torso kinematics for volunteers who were repositioned from a leaning-forward posture and exposed to braking were compared with their preferred upright postures (Event D) (Fig. 8). A second comparison can be made with volunteers who experienced braking while restrained by an activated B-post belt in an upright posture (Event I, Fig. 8 and Fig. E 22. This comparison reveals relatively small differences between the two groups: at ~750 ms after the initiation of PT and braking, the upper torso of the volunteers repositioned from the leaning-forward posture was only ~90 mm anterior and 10° flexed relative to upright and for similar belt PT forces (Fig. E 23, Table F 3). It can be noted that the CPVM muscles of volunteer exposed to braking were activated to a significantly greater extent when repositioned (Event D) compared to belt activation when in upright (Event I) (Fig. E 24).

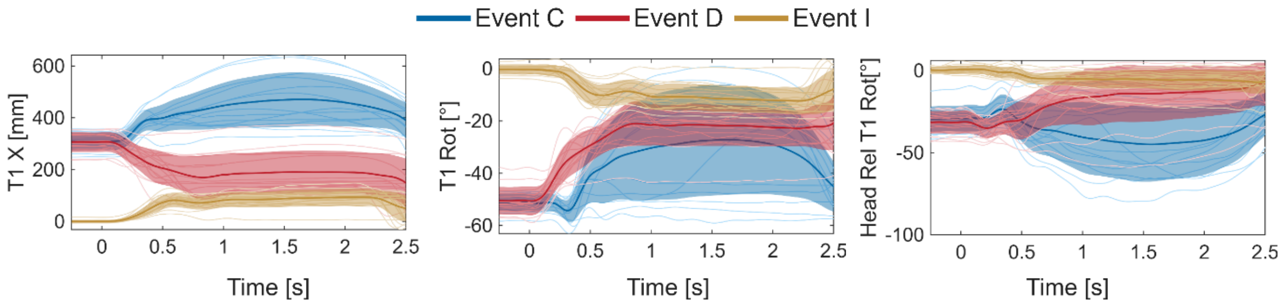

Fig. 8. Displacements of volunteers exposed to braking. Forward-leaning posture when restrained by a standard belt (Event C, red) vs Forward-leaning posture when repositioned by PT belt (Event D, blue) vs Upright posture when repositioned by PT belt (Event I, yellow). B-post belt geometry.

In contrast, without repositioning, the upper torso of leaning forward occupants (Event C) translated an additional 150 mm forward and rotated forward by ~10° immediately after braking onset. Later in the Event, volunteers appeared to straighten their backs (T1 Rot, Fig. 8), which is also reflected in the 12° forward rotation of the pelvis (Fig. E 22). Overall, the PT system reduced forward torso displacement by more than 250 mm compared with no repositioning conditions (Event C vs D, Fig. 8).

Q8 - Do occupants respond differently to braking depending on their initial posture?

When no PT activation was applied and belt conditions were comparable (Fig. E 26), the average leaning-forward volunteer remained almost 300 mm anterior to the average upright volunteer during braking (Fig. 9), measured from 500 ms to 2500 ms after brake onset. Notably, pelvic rotations were similar between the two groups: in both cases, the pelvises rotated forward by ~11° (Fig. E 25.

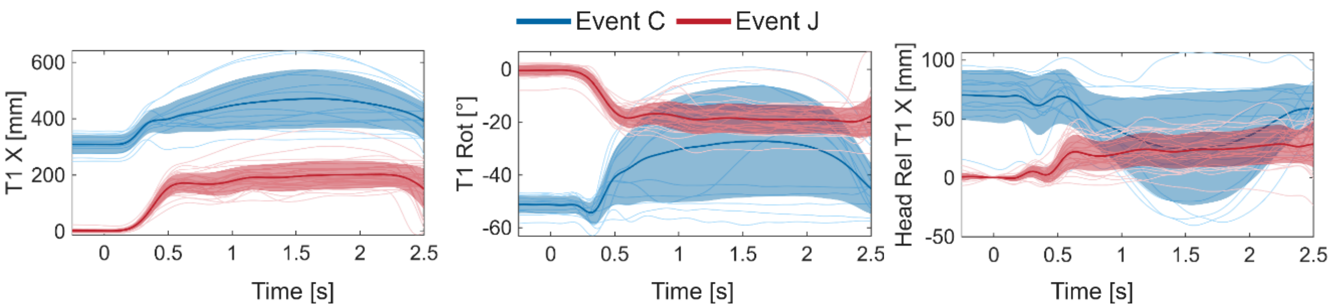

Fig. 9. Displacements for volunteers exposed to braking while restrained by a standard belt in B-post geometry. Forward-leaning (Event C, red) vs Upright posture (Event J, blue).

Q9 - Does belt geometry influence occupant response when seated in an upright posture?

Upright volunteers experienced significantly less forward torso motion when restrained by the BIS belt compared with the B-post belt during braking (Fig. E 20, Table F 1). However, the BIS belt was associated with greater neck flexion, despite smaller increase in lap-belt force (Fig. E 21).

Q10 - What is the effect of belt pre-tensioning when the occupant is in an upright posture?

PT belt activation significantly reduced the upper torso forward excursion of upright volunteers by ~100 mm during braking (Fig. E 18, Table F 1), corresponding to a 120 mm difference in belt pay-out for an activated (−80 mm) relative non-activated belt (+ 40 mm) (Fig. E 19).

IV. DISCUSSION

The primary aim of this study was to investigate the effectiveness of reversible belt pre-tensioning in repositioning forward-leaning occupants in a vehicle environment. The volunteer experiments were designed both to improve understanding of occupant responses during repositioning and to provide tuning and validation data for active HBMs. Sixteen volunteers underwent both constant speed and controlled braking conditions at 70 km/h in upright (25°) and forward-leaning (−15°) postures, using BIS and B-post belt configurations. Reversible pre-tensioning (250 N or 500 N), triggered immediately after acceleration onset, was applied to pull forward-leaning volunteers back toward their preferred upright posture while upper body kinematics, pelvis rotations and muscle activity were recorded.

In forward-leaning tests, volunteers began with their upper torsos positioned ~300 mm forward of upright. During constant speed travel, the B-post belt reduced this forward displacement to ~50 mm within 500 ms, while the BIS geometry achieved near complete repositioning. When braking occurred simultaneously, the repositioning response slowed and volunteers´ upper torsos remained ~90 mm forward preferred upright posture. In some individuals, elevated muscle tension further limited the repositioning. No significant sex-based differences were observed. Throughout the repositioning phase, flexor muscles were more active than extensors, indicating that volunteers tended to resist the belt induced motion rather than follow it passively.

Collectively, this work provides a detailed dataset on volunteer repositioning from forward-leaning postures at 70 km/h, including scenarios with controlled braking, and offers valuable input for the tuning and validation of active HBMs.

Compared to Similar Studies

The volunteer responses observed in this study show partial agreement with previously published findings. Witmer *et al.* [16] examined belt activation without any vehicle motion and reported that forward-leaning volunteers moved 79 mm rearward after 350 ms following a 300 N PT activation. In the present study, volunteers traveling at constant speed moved ~120 mm at the same time point using a 250 N PT setting. Graci *et al.* [4] found that volunteers' trunks (near the sternal notch) moved ~86 mm rearward at 500 ms after a 300 N PT activation combined with 250 ms of a 0.95 g rearward seat-base acceleration. Although no identical scenario exists here, their results can be loosely compared to the current average T1 rearward displacement at 500 ms: ~190 mm for low-level PT without braking, ~250 mm and for high-level PT without braking. Thus, volunteers in this study consistently moved more.

Several factors likely contributed to these differences. Volunteers in [4] and [16] were younger, tested outside a vehicle, and adopted a posture that was closer to upright (22° vs. 40° torso angle change from upright seating). Although age-related effects on muscle activation may have been modest, the more upright posture likely reduced the belt's effective resultant force on the upper torso. Furthermore, the braking/acceleration applied in [4] would have limited rearward displacement. In the present study, the upper torso moved 162 mm rearward at 500 ms under high-level PT combined with 0.8 g braking—still greater than in [4], but plausibly due to the higher PT load. Notably, the velocity change at 500 ms in the current study was roughly twice that in theirs. Overall, these findings suggest that the volunteers in the current study were less prepared than those in [4] and [16], and that flexor muscle activity may have been lower in the current study owing to the participants´ higher average age.

A simulation study by [6] suggested that a 600 N PT could reposition an occupant up to 220 mm within 200 ms from a -29° forward-leaning posture compared to upright seating during emergency braking. This compares poorly to the present findings, where volunteers moved only ~40 mm rearward within the same time frame with simultaneous PT activation and braking. However, methodological differences between the studies prevent direct comparisons.

In summary, volunteer motion magnitudes in this study align only partially with previous findings. Differences in posture, environment, PT levels, and applied vehicle or sled accelerations strongly influence outcomes and limit direct cross-study comparisons.

Pelvis Orientation

Belt–pelvis fit quality could not be evaluated, nor its potential deterioration during repositioning. However, measured changes in pelvis orientation provide indirect insight into the influence of belt activation on pelvic angular kinematics.

Belt pre-tensioning rotated the pelvis rearward by approximately 8–12°. This rearward rotation may affect the belt's ability to remain properly positioned over the pelvis during a sub-sequent crash. The volunteers began in a substantially forward-leaning posture (estimated to −40° forward of the upright), but the associated pelvic rotation in this posture could not be measured; therefore, their absolute pelvis orientation could not be established in this study.

If one assumes, hypothetically, that the pelvis rotated 20° forward when volunteers adopted the leaning-forward posture, the pelvis orientation after pre-tensioner activation would be approximately 8–12° forward relative to that in upright seating. For comparison, during braking with a traditional belt system, the pelvis rotated on average forward by about 12° in this study.

Male vs female responses

Almost no statistically significant sex differences were observed in EMG activity, and only minor differences were found in kinematic responses. These findings are consistent with previous studies examining repositioning from a forward-leaning to an upright posture, which likewise reported no sex-related differences [4][16]. However, research examining volunteer responses during evasive manoeuvres has identified sex-based differences [9][11], while others have reported similar displacement patterns for males and females during braking events or frontal crashes [7-9]. Collectively, these mixed findings suggest that sex effects may be task-specific and context-dependent. Future studies with larger sample sizes are therefore needed to clarify whether sex influences occupant response during PT-belt-assisted repositioning.

In the present study, EMG data indicate that males and females activated the studied muscles similarly during repositioning from a forward-leaning posture to an upright seating position induced by an active belt system. Consequently, observed differences in kinematic response were likely primarily attributable to differences in anthropometry, such as stature and body mass (the average men in the tested population were 9 cm taller and 11 kg heavier than the average female), rather than intrinsic sex-related neuromuscular differences. This supports the comparison of events using datasets that include both males and females, provided that the sex proportions are reasonably similar across events.

Analysis of kinematic responses further showed that, in the majority of events, there were no statistically significant differences between sexes. This overall similarity supports combining male and female data for most conditions.

Nevertheless, in a subset of repositioning events (D, F, and G), statistically significant sex-related differences were observed. These findings were consistent irrespective of whether the analysis included change in positions (Table E 4) and the data analysis included also variations in initial posture relative to the preferred position (Table E 1). In these events, females repositioned more rapidly and displaced more, as indicated by greater rearward motions (T1 x-displacements, Fig. E 5), compared with males.

These results should, however, be interpreted with caution. Multiple comparisons were conducted without any adjustment (e.g. Bonferroni correction). One way to mitigate this limitation is to focus on the most relevant outcome measure, T1 x-displacement, where sex differences were limited and not consistently observed across events.

It could be argued that the male-to-female proportions were sufficiently similar to enable valid event-to-event comparisons. However, the proportions of females varied between 31% to 50% across events (Table E 5), which may have influenced the results. The male-female proportion in each event should also be taken into account when applying the dataset to human body model evaluations.

In conclusion, given the limited number of tests per event and the small and inconsistent sex-related differences observed, male and female data were combined for analyses of Q2 through Q10.

Muscle Activation

Prior investigations into PT-belt activation for repositioning forward-leaning occupants have not included detailed analyses of trunk muscle activation [4][16]. Without comprehensive muscle activation data, it is not possible to differentiate occupant kinematics resulting from voluntary motion from those produced by external loading. A notable exception is the study by [16][5], who reported MVIC-normalised muscle activity for the arms, legs, and shoulder regions, as well as for the SCM and trapezius muscles in the cervical and upper thoracic regions. In the present study, MVIC-normalised muscle activation was also recorded to support ongoing efforts in the development of active human body models (HBMs). Although this work complements that of [16] by incorporating measurements from abdominal and lower-back musculature, the dataset is limited to four muscle pairs. To achieve a more comprehensive characterisation of occupant muscular response, future experimental efforts could include additional trunk extensors, flexors, and stabilising muscle groups.

Most volunteers activated their flexor muscles to a greater extent than their extensor muscles during the transition from a forward-leaning to an upright posture. The volunteer tests were performed in random order, except for the sequence in which the BIS and P-post belts were switched, which occurred only once per volunteer. Thus, individual volunteers experienced a mixture of low-level PT, high-level PT, and no-activation conditions. Despite the possibility of some anticipatory awareness, additional observations suggest that the increased flexor activation may reflect a reflexive response rather than deliberate resistance. The findings indicate that future studies should consider recruiting highly fit volunteers to better determine whether higher pre-tensioning forces then those used in this study are required to effectively reposition the entire occupant population.

A few volunteers reported that repeated belt loading on the shoulder felt uncomfortable, but the EMG data indicate that the volunteers did not activate the back muscles (LPVM) to reduce this.

In the volunteer studies conducted by [4], the highest muscle activity was observed in the SCM. A similar pattern was found in the present study. However, it should be noted that the comparisons made here differ from those in [4]: in our study, SCM activation was evaluated relative to neck extensors and trunk flexor and extensor muscles, whereas their analyses compared the SCM activity with other muscle groups.

Limitations

It can be argued that the forward-leaning posture used in this study was relatively extreme—approximately 40° forward of the upright seating position. However, this posture is comparable to that employed in the volunteer study by [16] and only ~10° greater than the torso angle considered in the mathematical simulation study by [6]. Because only a single forward-leaning posture was examined, it remains uncertain how effectively the applied pre-tensioning levels would reposition occupants exhibiting less pronounced forward leaning. Future research could therefore investigate a broader spectrum of forward-leaning postures to identify the lower thresholds at which the tested pre-tensioning forces remain effective.

This study did not evaluate the influence of pretensioner (PT) onset timing relative to the initiation of braking. In the present tests, the PT activation commenced ~50 ms after brake initiation. The brake robot achieved a considerable deceleration (0.8 g) in ~300 ms, while the high-level PT activation terminated at ~600 ms, coinciding with the application of simultaneous braking. If the PT system were to activate slightly before the onset of braking, the belt-force buildup, that stops the pre-tensioning system from pulling in the belt, would occur later in the manoeuvre, and the resulting occupant response would likely resemble the behaviour observed in the constant-speed tests. This interpretation is supported by the finding that low-level pre-tensioning was able to reposition occupants during the constant-speed tests almost as effectively as high-level pre-tensioning.

During testing, several volunteers examined the surroundings of the test track, including visible rubber markings, and learned that tests were conducted only on straight road segments—primarily three specific stretches. Based on their comments during testing, it appeared that some volunteers were able to anticipate the onset of an event which could have influenced their responses. However, this issue was less pronounced in tests where volunteers were leaning forward, as their visibility of the surroundings was reduced, for which several volunteers reported being startled by the belt activation.

Pelvis orientation was measured using a gyroscope attached to the skin near the upper sacral region. Due to minor sensor drift, it was not possible to obtain an absolute orientation of the pelvis; instead, only rotational changes relative to the onset of the event could be reliably determined. Consequently, the final pelvis orientation after repositioning can only be speculated upon. Future studies could employ a gravity-based sensor in combination with the gyroscope, or implement enhanced gyroscope-processing methods, to enable accurate estimation of absolute pelvic orientation.

In this study we used discrete values in the statistical analysis which were average responses for a given time window, hence results could be influenced by the choice of time window.

V. CONCLUSION

Activation of a reversible belt pre-tension system at both a low (250 N) and high (500 N) level could reposition a passenger occupant in a forward-leaning posture with the upper torso ~300 mm forward of upright. If the pre-tensioning was simultaneous as a braking intervention, the effectiveness of the repositioning was reduced. During repositioning, the flexor muscles activated more than the extensors, indicating that volunteers tended to resist the motion imposed by the belt pre-tension. A Belt-in-Seat geometry with the belt closer to the shoulder of the occupant was more effective than a traditional B-post geometry in repositioning the occupant. This work provides a dataset on volunteer repositioning from forward-leaning, including scenarios involving pre-crash braking, suitable for Human Body Model evaluation.

VI. ACKNOWLEDGEMENTS

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Generative artificial intelligence tools (Microsoft 365 Copilot, 19.2603.48201.0) were used to support language editing. All scientific content, interpretations, and conclusions were developed, reviewed, and validated by the authors, who take full responsibility for the accuracy and integrity of the work.

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VIII. Appendix A – Volunteer Anthropometry and Demography

TABLE A 1.
VOLUNTEER ANTHROPOMETRY AND DEMOGRAPHY. SD = STANDARD DEVIATION.

	Female			Male		
	Minimum	Average (SD)	Maximum	Minimum	Average (SD)	Maximum
Age (years)	24	30 (8.3)	48	24	37 (12.5)	57
Stature (cm]	157	169 (7.4)	181	168	178 (8.1)	191
BMI (kg/m^2)	21	23 (1.5)	25	23	24 (1.4)	28
Seated height (cm)	82	80(4.2)	94	90	93 (3.1)	98

IX. Appendix B - Surface Electromyography and Maximum Voluntary Isometric Contractions

Surface electromyography (EMG) electrodes were placed bilaterally on four muscle groups (Fig. B 1). For the sternocleidomastoid (SCM), two electrodes were positioned side by side at one-third of the distance from the suprasternal notch to the mastoid process. For the cervical paravertebral muscles (CPVM), electrodes were centred at the C4 level, approximately 20 mm lateral to the midline. For the longissimus paravertebral muscles (LPVM), electrodes were centred at the L1 level, approximately 40 mm lateral to the midline. For the rectus abdominis (RA), electrodes were placed above and below the umbilicus, approximately 45 mm lateral to the midline on each side. A reference electrode was placed on the right anterior superior iliac spine and a ground electrode on the left anterior superior iliac spine.

Before electrode application, the skin was shaved and cleaned with 70% ethanol. EMG signals were sampled at 2048 Hz using a Grael unit biosignal recorder (Compumedics, Abbotsford, Australia). Paired electrodes (Blue Sensor 72015/10; Ambu A/S, Ballerup, Denmark) with 22 mm inter-electrode spacing were used, and leads were secured with surgical tape. The biosignal recorder was placed in a portable plastic box carried by the volunteer when moving between test locations.

Maximum voluntary isometric contractions (MVICs) were collected before the in-vehicle tests to normalise EMG amplitudes. A dedicated test rig (Fig. B 1) enabled isometric neck and trunk exertions while maintaining an occupant-like posture, with the distal femur and feet restrained. Volunteers performed neck flexion and neck extension, and trunk flexion and extension. Each task consisted of 3 s at ~50% effort followed by 3 s at maximal effort, repeated twice.

Force during MVICs was measured using a TTL-500 (Transducer Techniques, Temecula, CA, USA). Real-time force output was displayed on a monitor to provide visual feedback for the volunteers.

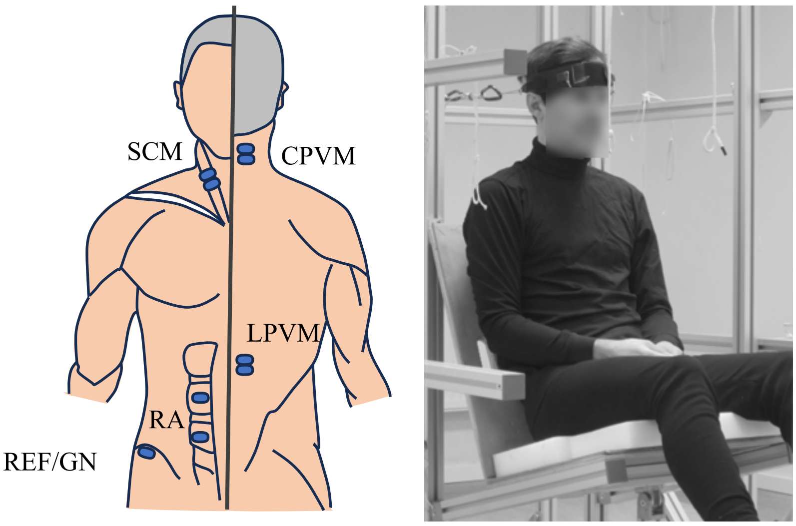


Fig. B 1 Electrode placement (left) body front and body rear. Volunteer in MVIC test rig (right).

X. Appendix C – Vehicle kinematics

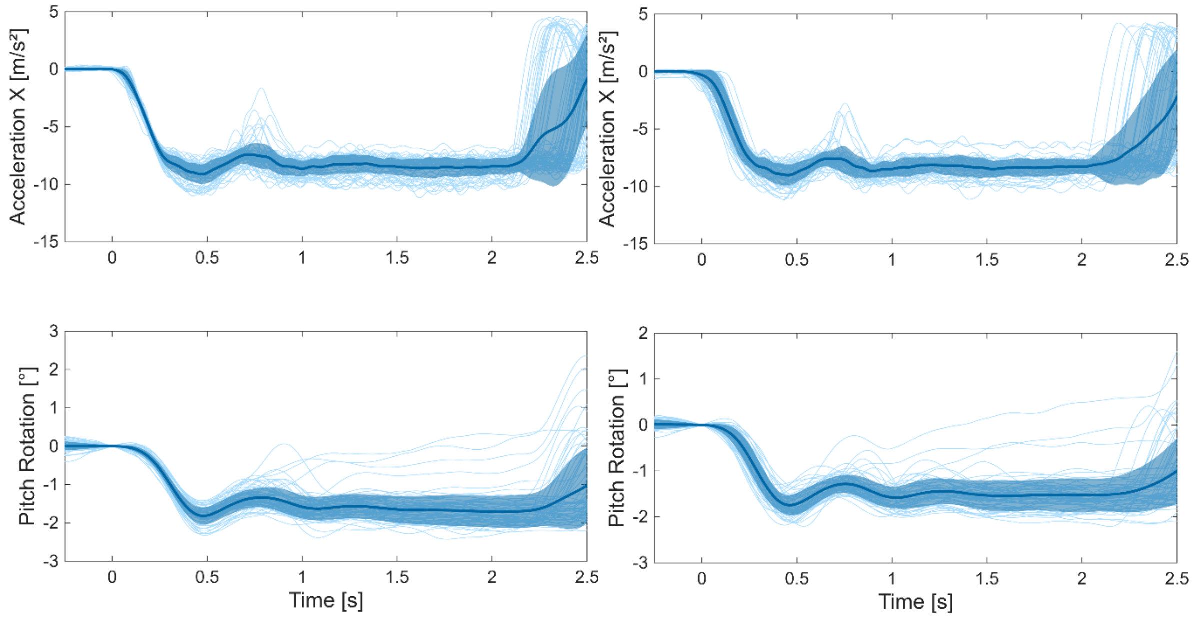


Fig. C 1. Vehicle deceleration (top) and pitch (bottom) in Events C, H, I, and J (left) and in Events B and D (right).

XI. Appendix D - Data Analysis

Head CoG displacements were estimated in each test from digitised video data, the location of the external auditory duct relative to the video markers mounted on the side of the volunteer´s head and published data on the distance between the external auditory duct and the head CoG (Walker et al. 1973; Beier et al. 1980; Yoganandan et al. 2009). The components used were x = 8.7 mm *Z* = 26.8 mm for males and *x* = 0.2 mm and z = 29.1 mm for females.

T1 displacements were estimated from digitised video data; the average value of C7-T1 skin marker data and the sternal skin video marker data were used.

Table D 1 presents time windows used for averaged calculations prior to ANOVA analysis.

TABLE D 1.
TIME WINDOWS USED IN THE ANOVA ANALYSIS

Signal	Discrete value
Kinematics from video data and pelvis gyro	Average values for 0-1 s window
EMG	Average activity for 0-0.5 s window
Seatbelt data	Average rotation for 0-0.5 s window

XII. Appendix E – Answering specific questions - complementary figures

Appendix E1 – Should analyses be performed separately for male and female participants?

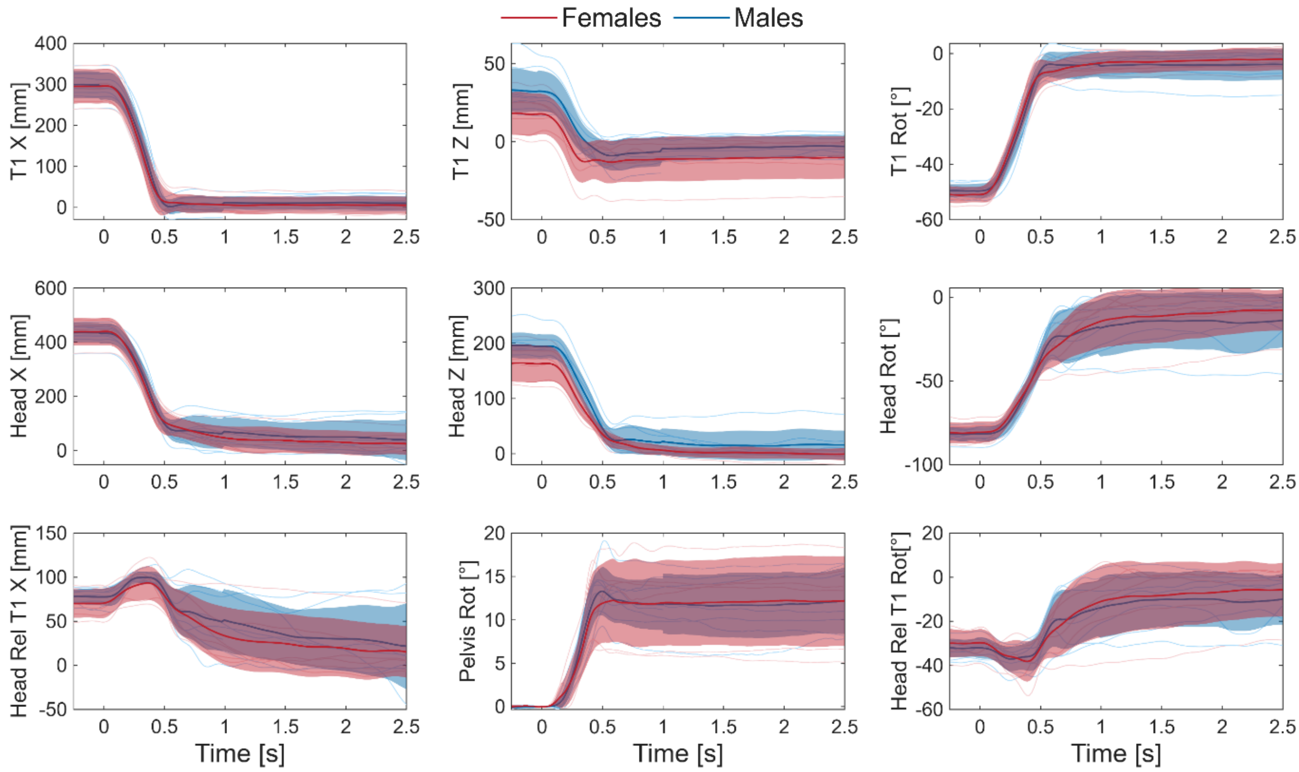


Fig. E 1. Displacements for volunteers in forward-leaning posture when repositioned by PT belts with BIS geometry at constant vehicle speed (Event E). Females (red) vs Males (blue). All data, except for pelvis rotations, compared to preferred upright posture.

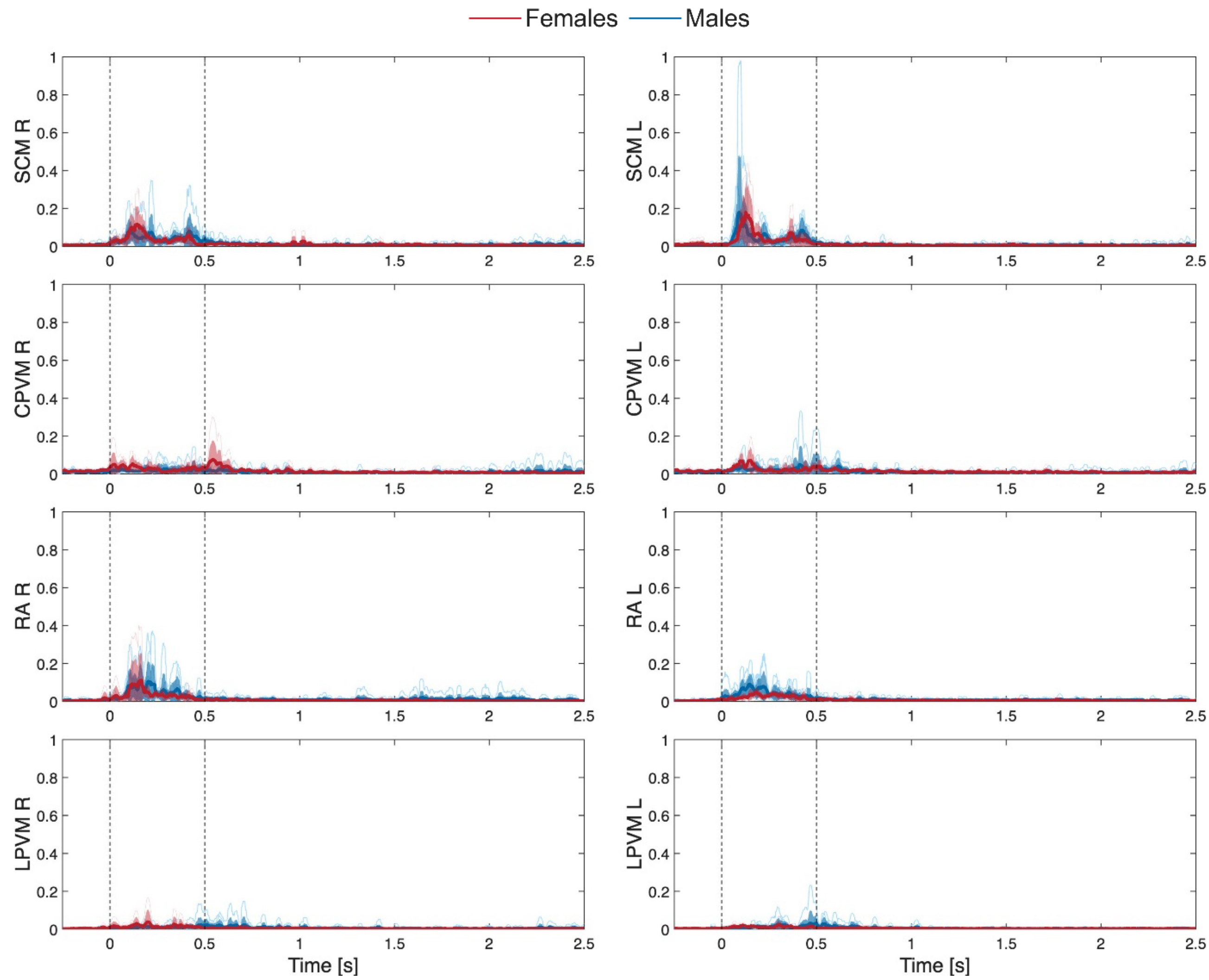


Fig. E 2. EMG for volunteers in forward-leaning posture when repositioned by PT belts with BIS geometry at constant vehicle speed (Event E). Females (red) vs Males (blue).

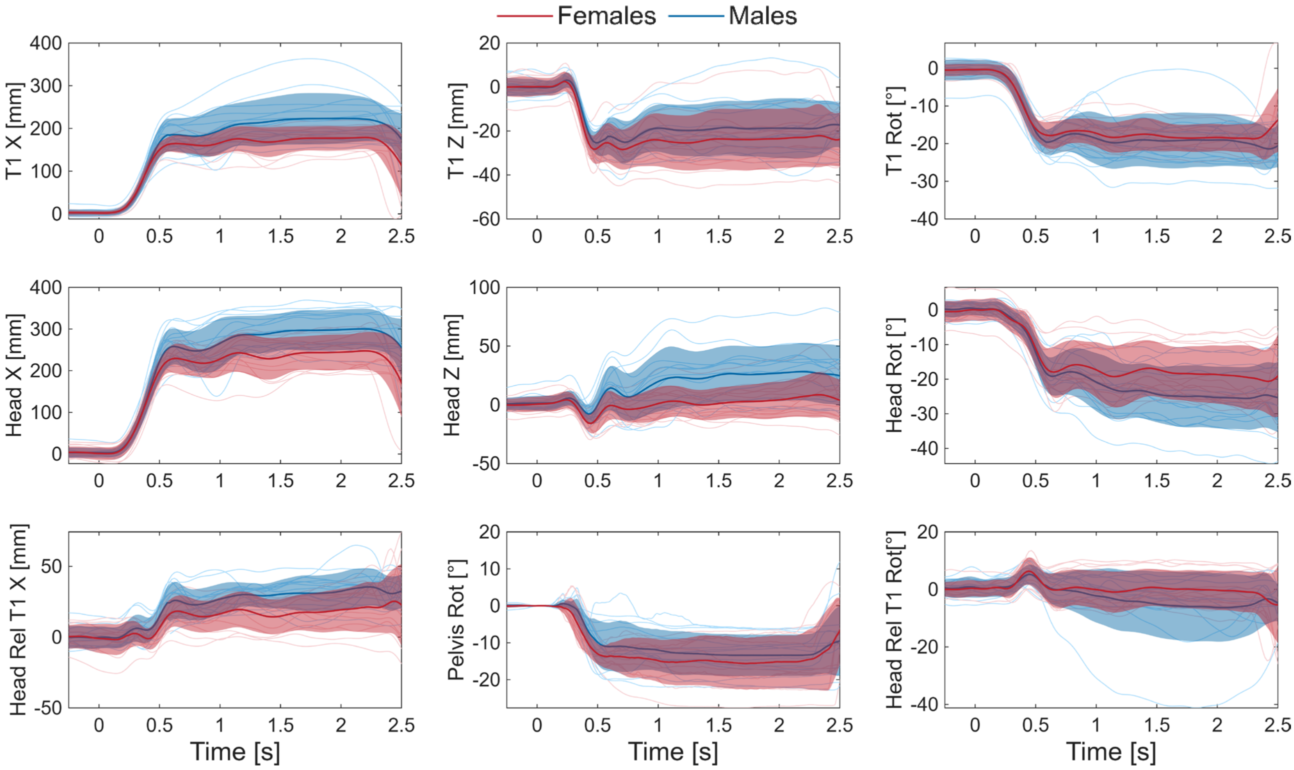


Fig. E 3. Displacements for volunteers in upright posture restrained by standard belt in B-post geometry and exposed to braking (Event J). Females (red) vs Males (blue).

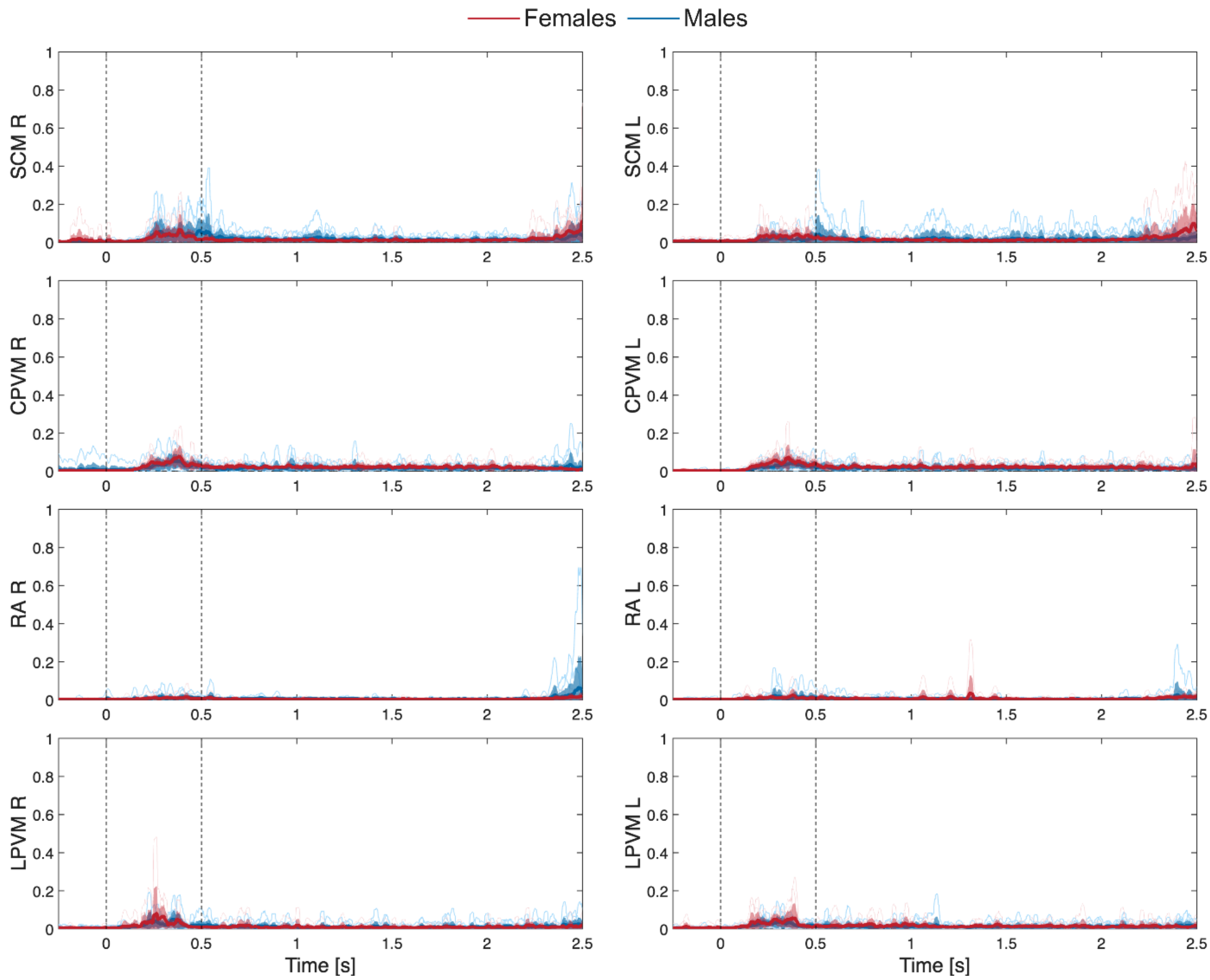


Fig. E 4. EMG for volunteers in upright posture restrained by standard belt in B-post geometry and exposed to braking (Event J). Females (red) vs Males (blue).

TABLE E 1.

KINEMATIC COMPARISONS BETWEEN MALE AND FEMALE PARTICIPANTS ARE PRESENTED, WITH ANOVA USED TO ASSESS BETWEEN-GROUP DIFFERENCES. UNDERLINED P-VALUES DENOTE RESULTS BELOW THE STATISTICAL SIGNIFICANCE THRESHOLD. DATA ANALYSED WERE KINEMATICS IN RELATION TO PREFERRED UPRIGHT POSTURE (EXCEPT FOR PELVIS ROTATIONS)

Event	T1 X	T1 Z	T1 Rot	Head X	Head Z	Head Rot	Head rel T1 Rot
B	0.55	0.50	0.65	0.50	0.08	0.49	0.66
C	0.49	0.09	0.88	0.95	<u>0.04</u>	0.96	0.97
D	<u>0.01</u>	0.06	0.21	<u>0.01</u>	<u>0.02</u>	0.35	0.75
E	0.41	0.09	0.46	0.42	0.06	0.50	0.76
F	<u>0.01</u>	0.24	<u>0.01</u>	<u>0.01</u>	<u>0.00</u>	<u>0.01</u>	0.06
G	<u>0.02</u>	0.38	<u>0.03</u>	<u>0.02</u>	0.11	0.19	0.85
H	0.22	0.27	0.22	0.87	0.94	0.89	0.18
I	0.25	0.20	0.32	0.16	0.39	0.32	0.65
J	<u>0.04</u>	0.84	0.26	<u>0.04</u>	<u>0.01</u>	0.32	0.99

TABLE E 2.
MUSCLE ACTIVITIES COMPARISONS BETWEEN MALE AND FEMALE PARTICIPANTS ARE PRESENTED, WITH ANOVA USED TO ASSESS BETWEEN-GROUP DIFFERENCES. UNDERLINED P-VALUES DENOTE RESULTS BELOW THE STATISTICAL SIGNIFICANCE THRESHOLD

Event	SCM_R	SCM_L	CPVM_R	CPVM_L	RA_R	RA_L	LPVM_R	LPVM_L
B	0.93	0.79	0.16	0.34	0.44	0.33	0.74	0.46
C	0.47	0.71	0.86	0.02	0.34	0.24	0.75	0.76
D	0.81	0.85	0.09	0.07	0.87	0.69	0.09	0.50
E	0.89	0.92	0.28	0.66	0.38	0.05	0.54	0.62
F	0.49	0.58	0.03	0.04	0.30	0.81	0.00	0.07
G	0.03	0.20	0.42	0.28	0.90	0.61	0.08	0.69
H	0.50	0.08	0.09	0.15	0.51	0.55	0.66	0.75
I	0.41	0.50	0.18	0.67	0.24	0.25	0.27	0.28
J	0.55	0.08	0.45	0.02	0.80	0.91	0.63	0.20

TABLE E 3.
BELT COMPARISONS BETWEEN MALE AND FEMALE PARTICIPANTS ARE PRESENTED, WITH ANOVA USED TO ASSESS BETWEEN-GROUP DIFFERENCES. UNDERLINED P-VALUES DENOTE RESULTS BELOW THE STATISTICAL SIGNIFICANCE THRESHOLD

Event	Diagonal belt force	Lap belt force	Belt pay-in
B	0.91	0.05	0.11
C	0.23	0.13	0.40
D	0.36	0.37	0.16
E	0.90	0.74	0.21
F	0.21	0.78	0.18
G	0.01	0.15	0.07
H	0.04	0.00	0.36
I	0.49	0.30	0.94
J	0.02	0.03	0.18

TABLE E 4.
KINEMATIC COMPARISONS BETWEEN MALE AND FEMALE PARTICIPANTS ARE PRESENTED, WITH ANOVA USED TO ASSESS BETWEEN-GROUP DIFFERENCES. UNDERLINED P-VALUES DENOTE RESULTS BELOW THE STATISTICAL SIGNIFICANCE THRESHOLD. DATA ANALYSED WERE CHANGES IN RELATION TO RESPONSES AT TIME ZERO

Event	T1 X	T1 Z	T1 Rot	Head X	Head Z	Head Rot	Head rel T1 Rot	Pelvis Rot
B	0.71	0.91	0.97	0.45	0.13	0.51	0.11	0.42
C	0.27	0.09	0.88	0.95	0.04	0.96	0.78	0.97
D	0.01	0.06	0.21	0.01	0.02	0.35	0.31	0.75
E	0.95	0.25	0.51	0.32	0.10	0.39	0.34	0.48
F	0.03	0.24	0.01	0.01	0.00	0.01	0.01	0.05
G	0.03	0.38	0.03	0.02	0.11	0.19	0.12	0.85
H	0.04	0.43	0.26	0.93	0.57	0.97	0.12	0.27
I	0.55	0.20	0.32	0.15	0.39	0.32	0.30	0.65
J	0.09	0.84	0.26	0.04	0.01	0.32	0.06	0.99

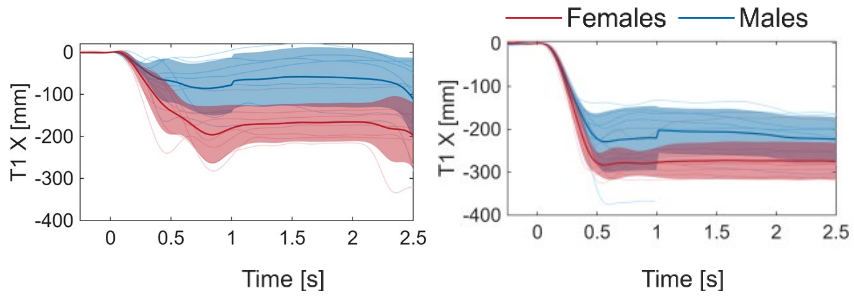


Fig. E 5. Change of T1 position in x-direction as a function of time for forward-leaning volunteers repositioned by high level pre-tensioning B-post belt during braking (Event D, left), repositioned by high level pre-tensioning B-post belt at constant vehicle speed (Event F, middle) and repositioned by low level pre-tensioning B-post belt at constant vehicle speed (Event G, right).

TABLE E 5.
NUMBER OF TESTS CARRIED OUT AND PRESENTED FOR EACH EVENT AND PROPORTIONS FEMALES

Event	Total number tested	Total number analysed	Proportion females (%)
B	17	13	46
C	16	14	50
D	18	15	40
E	18	15	40
F	18	16	38
G	13	13	38
H	28	24	46
I	15	13	31
J	29	26	46

Appendix E2 - Can a forward-leaning occupant be repositioned using belt pre-tensioning?

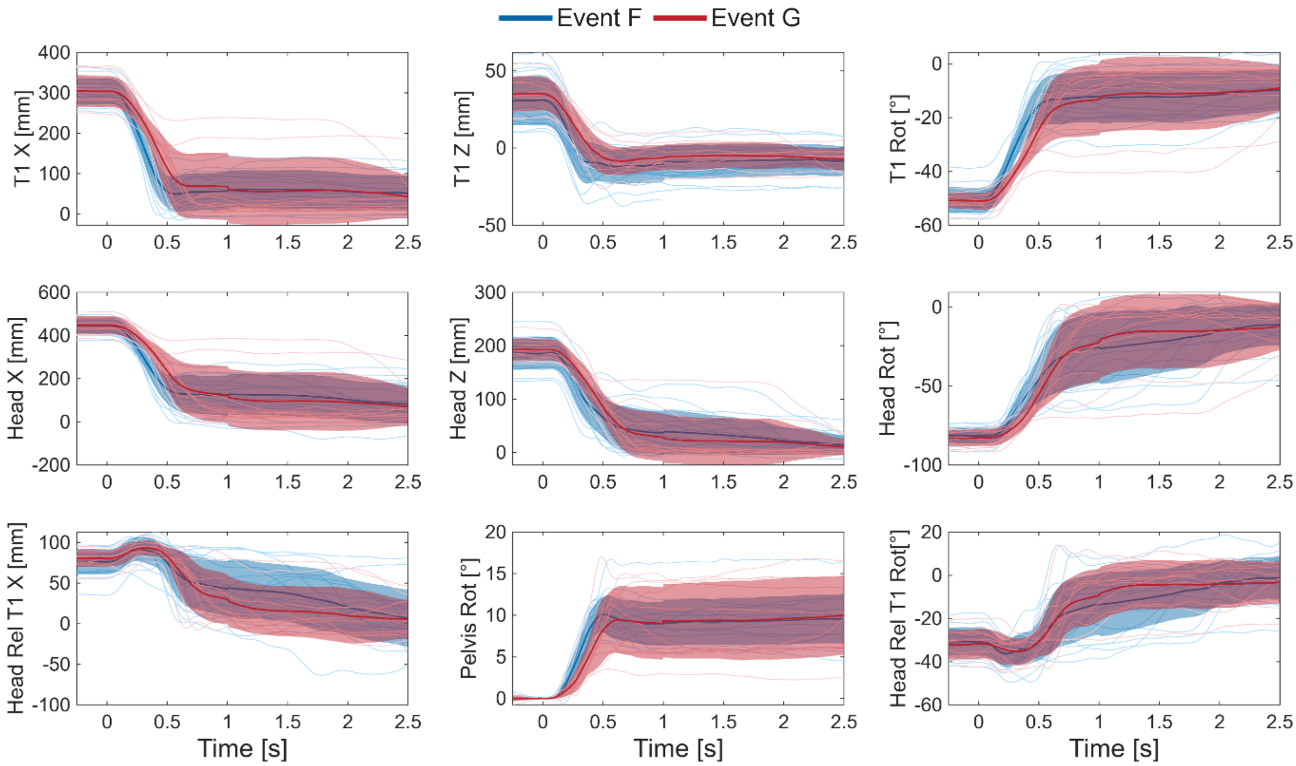


Fig. E 6. Displacements for volunteers in forward-leaning posture when repositioned by PT belts. High PT level (Event F, blue) vs Low PT level (Event G, red). B-post belt geometry and constant vehicle speed.

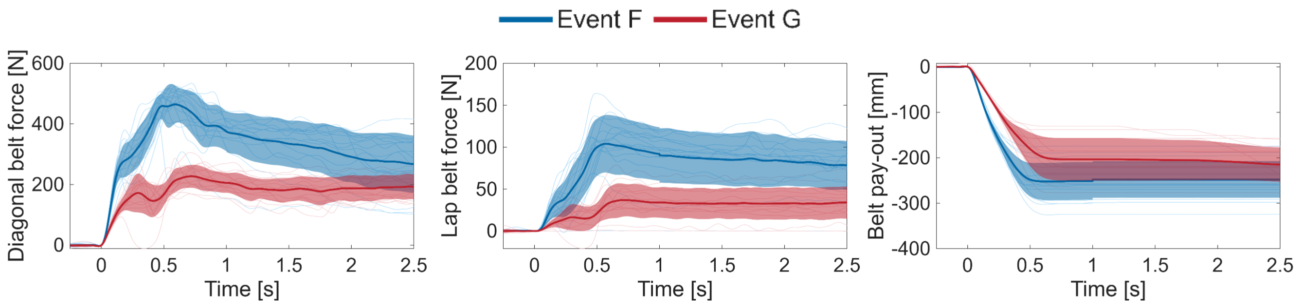


Fig. E 7. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers in forward-leaning posture when repositioned by PT belts. High PT level (Event F, blue) vs Low PT level (Event G, red). B-post belt geometry and constant vehicle speed.

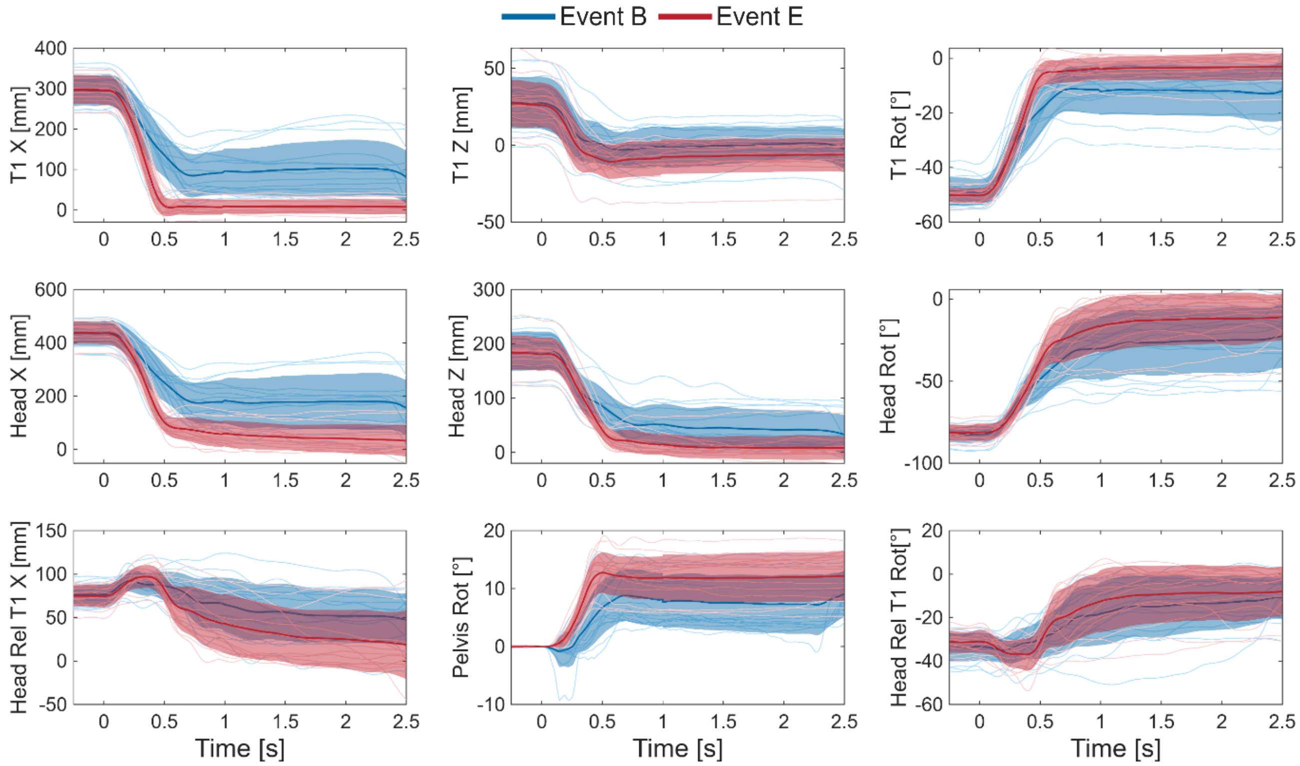


Fig. E 8. Displacements for volunteers in forward-leaning posture when repositioned by high-level PT belts. Braking (Event B, blue) vs Constant vehicle speed (Event E, red). BIS belt geometry.

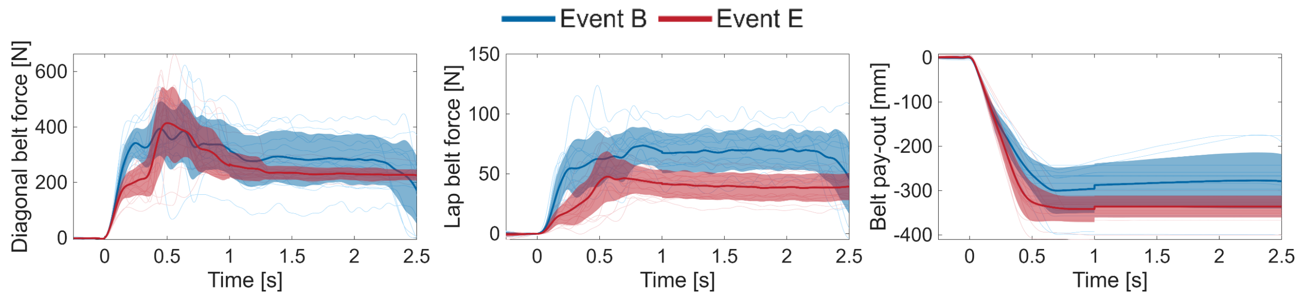


Fig. E 9. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers in forward-leaning posture when repositioned by high-level PT belts. Braking (Event B, blue) vs Constant vehicle speed (Event E, red). BIS belt geometry.

Appendix E4 - Does belt geometry influence the ability to reposition a forward-leaning occupant?

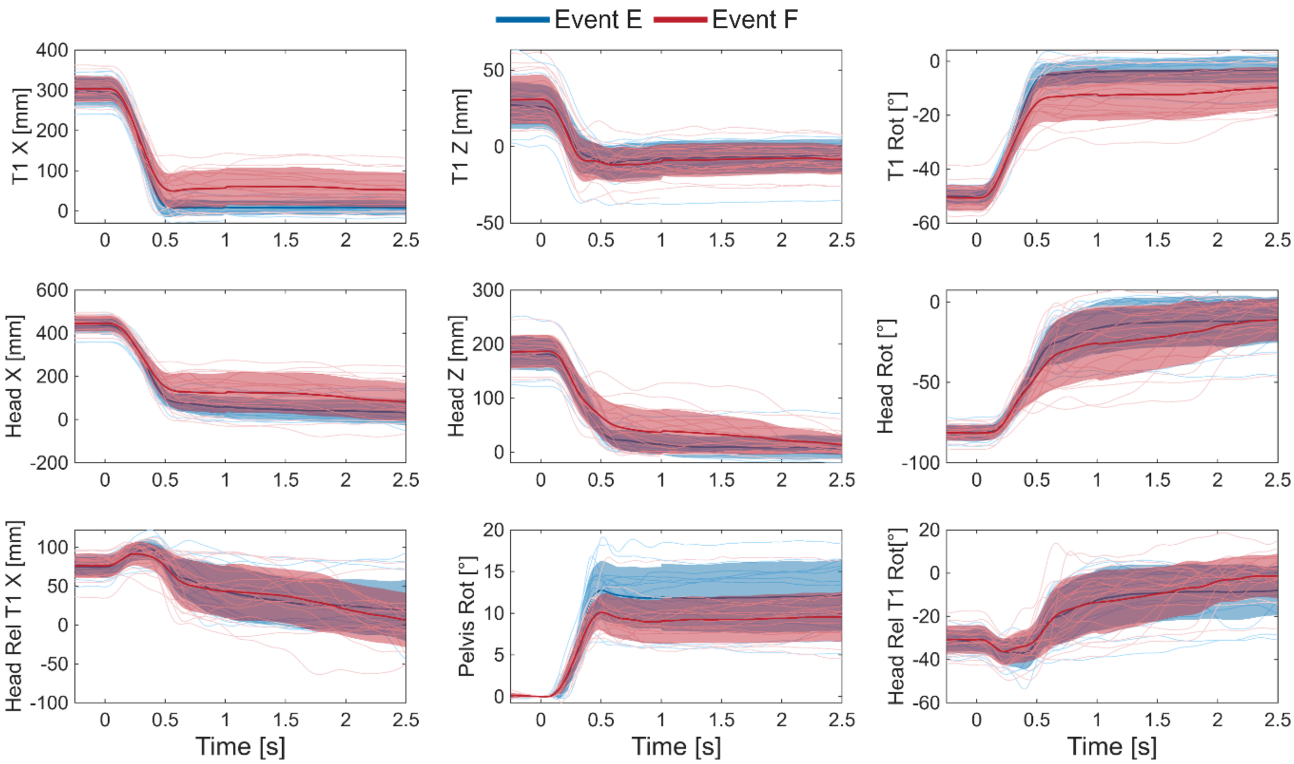


Fig. E 10. Displacements for volunteers in forward-leaning posture when repositioned by PT belts. BIS belt geometry (Event E, blue) vs B-post belt geometry (Event F, red). High PT level and constant vehicle speed.

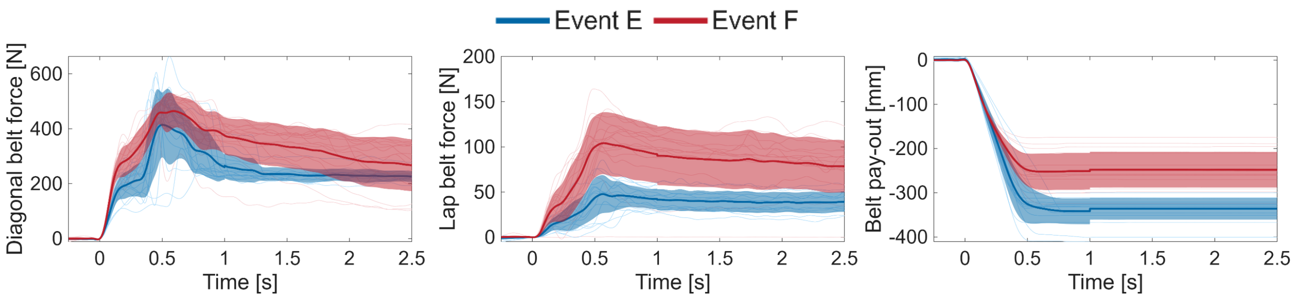


Fig. E 11. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers in forward-leaning posture when repositioned by PT belts. BIS belt geometry (Event E, blue) vs B-post belt geometry (Event F, red). High PT level and constant vehicle speed.

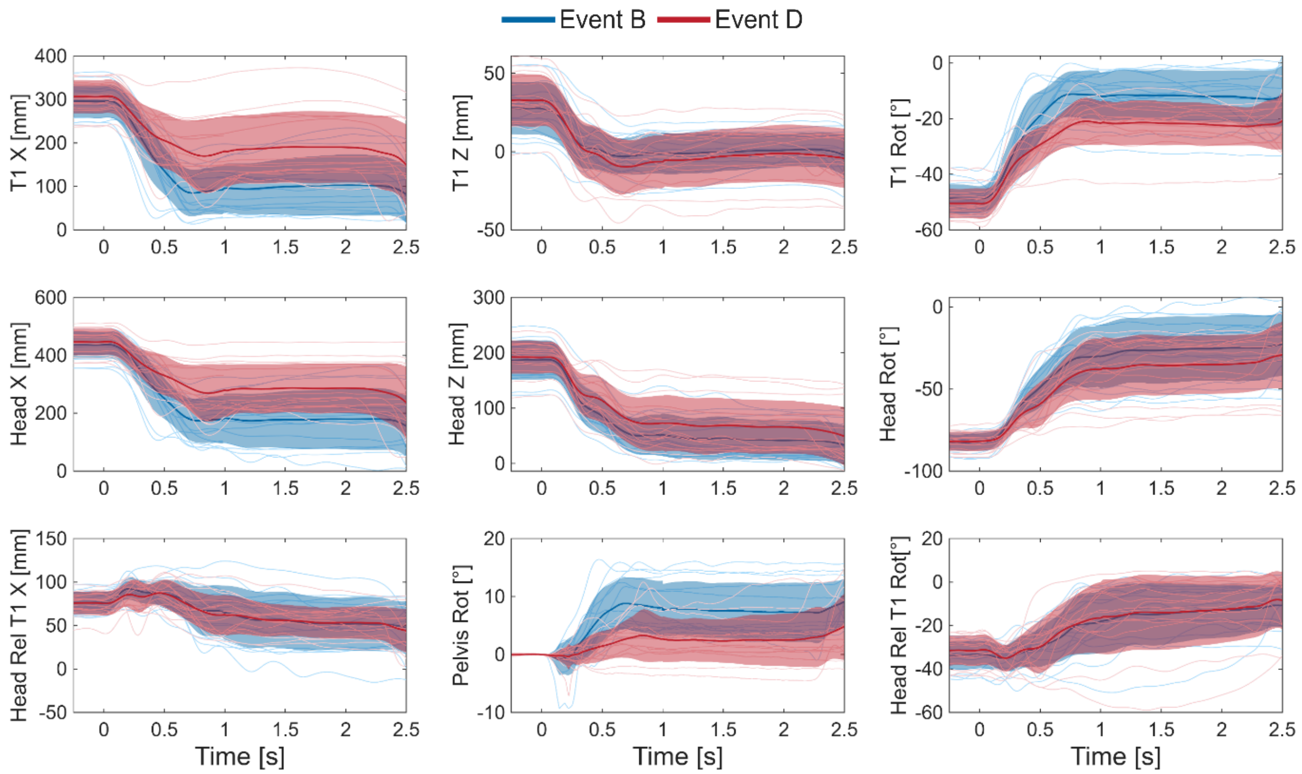


Fig. E 12. Displacements for volunteers in forward-leaning posture when repositioned by PT belts. BIS belt geometry (Event B, blue) vs B-post belt geometry (Event D, red). High PT level and braking.

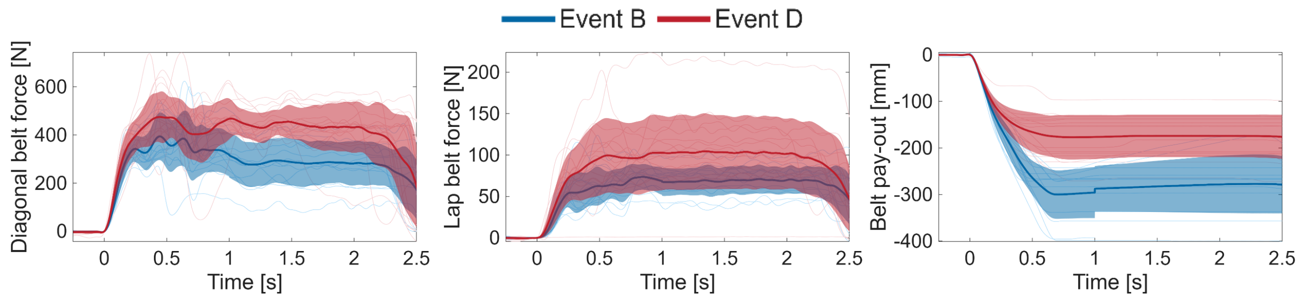


Fig. E 13. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers in forward-leaning posture when repositioned by PT belts. BIS belt geometry (Event B, blue) vs B-post belt geometry (Event D, red). High PT level and braking.

Appendix E6 - Does the repositioning intervention affect pelvis angle?

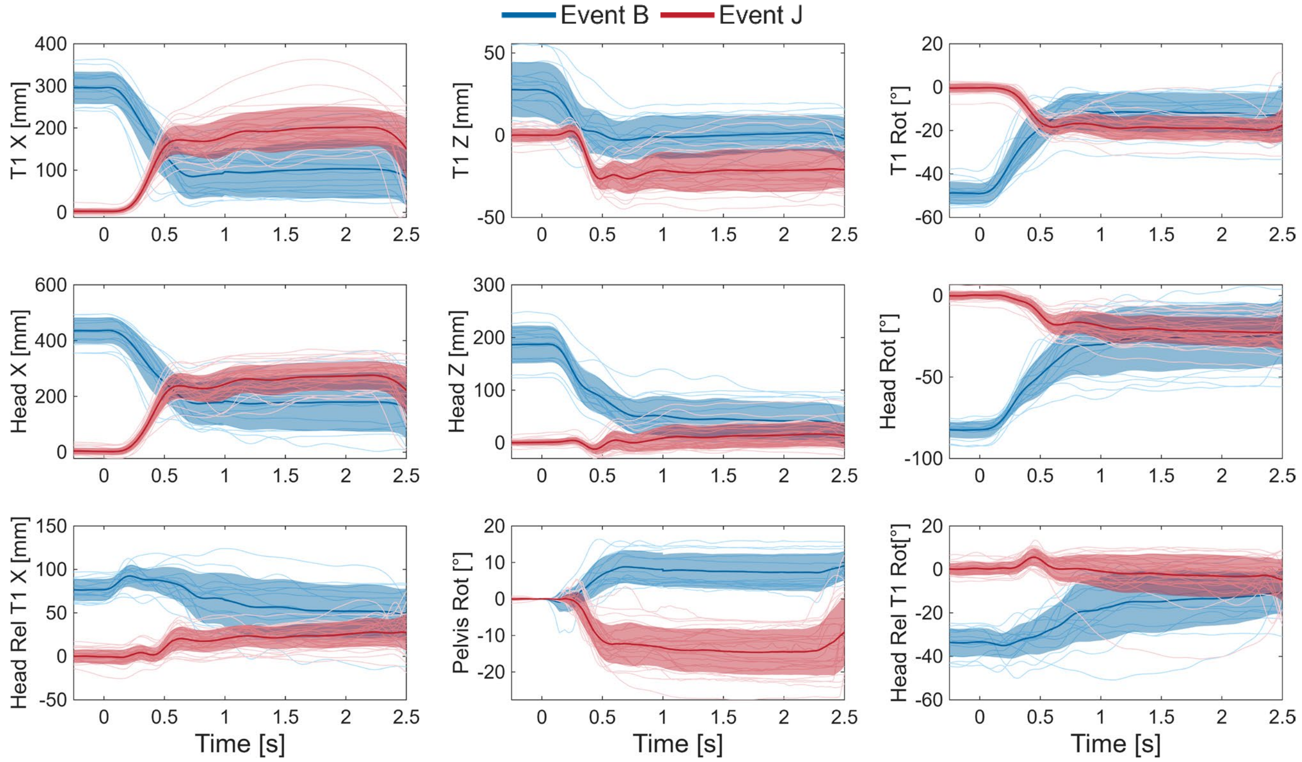


Fig. E 14. Displacements for volunteers repositioned by PT belts with BIS belt geometry and exposed to braking. Forward-leaning posture (Event B, blue) vs Upright posture (Event J, red).

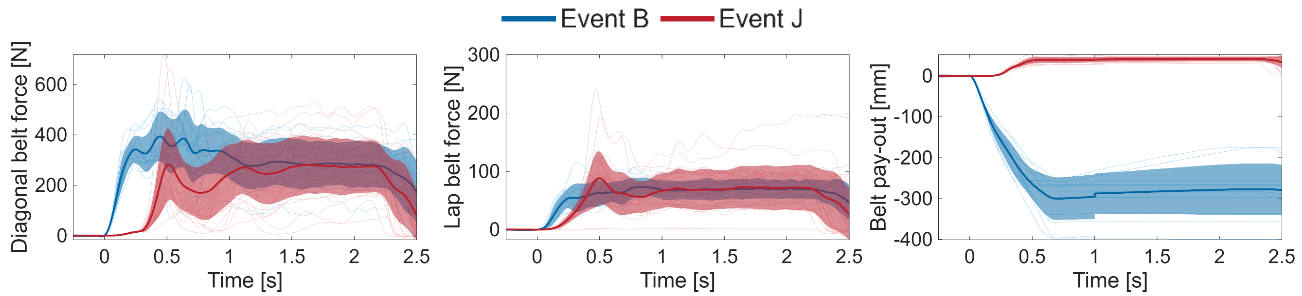


Fig. E 15. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers repositioned by PT belts with BIS belt geometry and exposed to braking. Forward-leaning posture (Event B, blue) vs Upright posture (Event J, red).

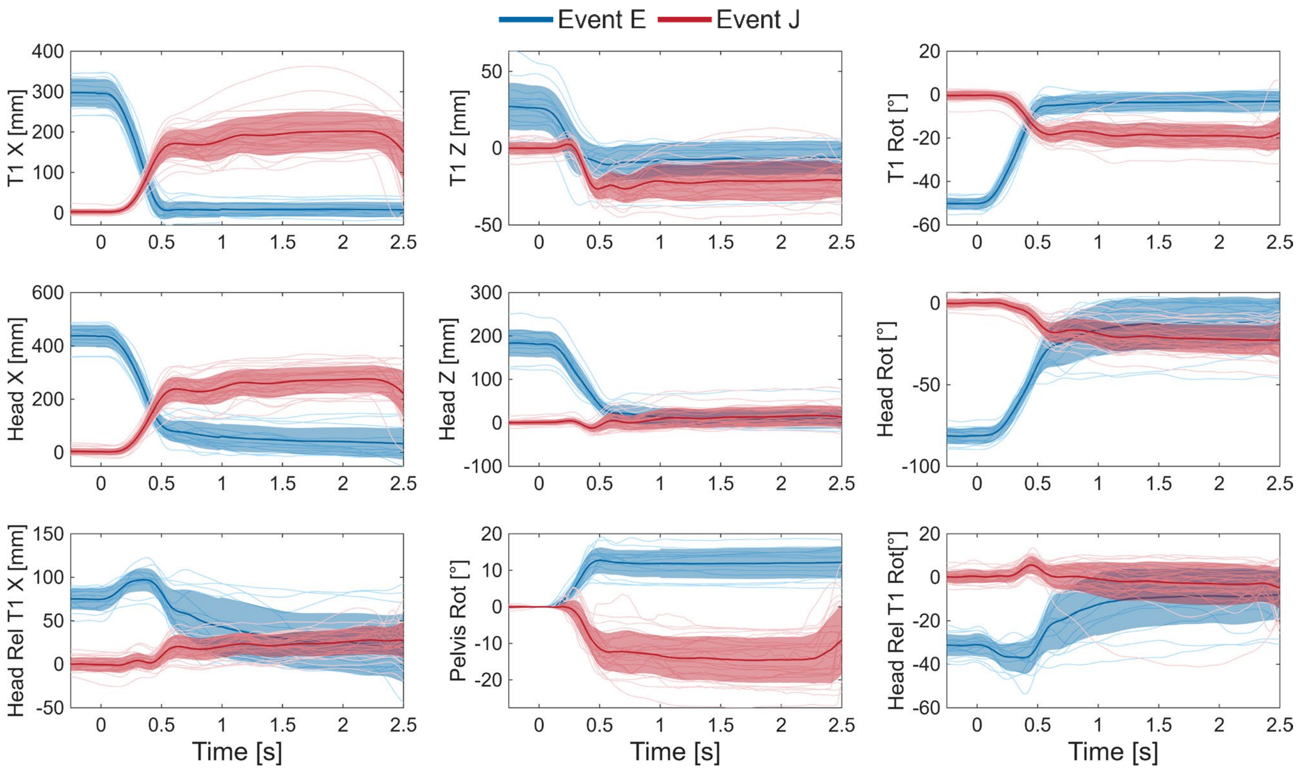


Fig. E 16. Displacements. Forward-leaning posture, constant vehicle speed, repositioned by PT, and belt BIS geometry (Event E, blue) vs Upright posture, exposed to braking, standard belt, and B-post geometry (Event J, red).

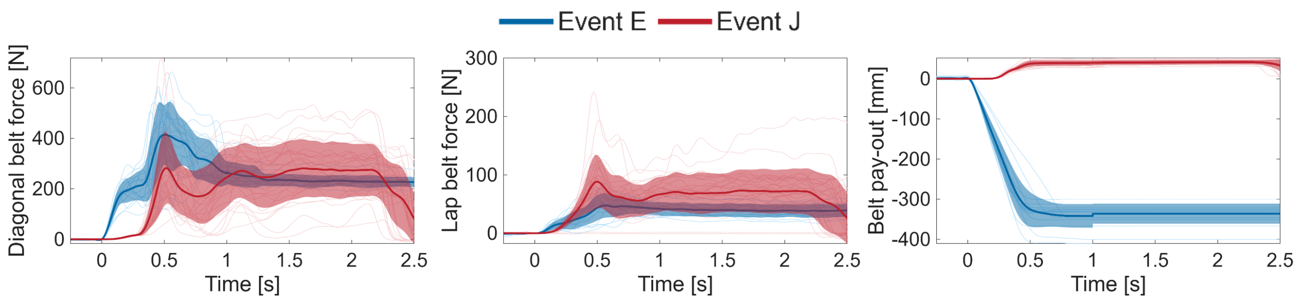


Fig. E 17. Diagonal and lap belt forces and pay-out (negative=pay-in). Forward-leaning posture, constant vehicle speed, repositioned by PT, and belt BIS geometry (Event E, blue) vs Upright posture, exposed to braking, standard belt, and B-post geometry (Event J, red).

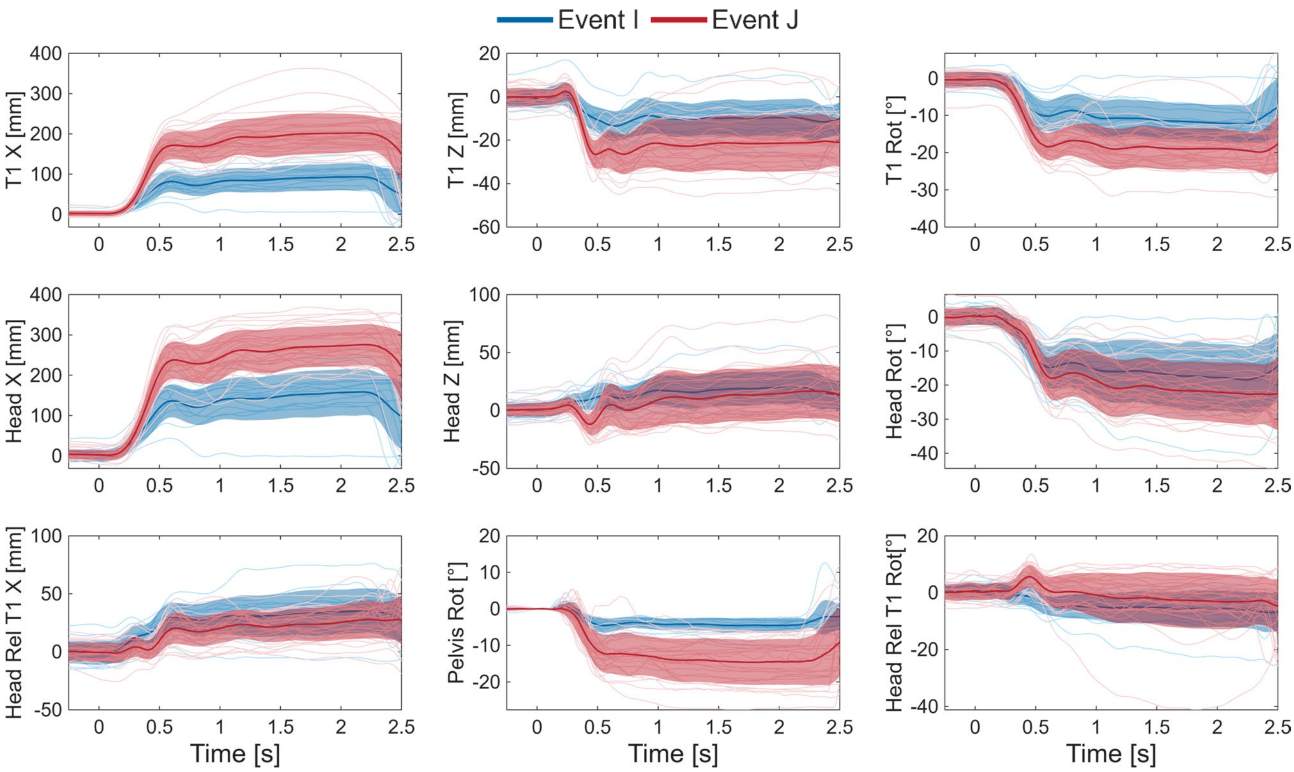


Fig. E 18. Displacements for volunteers in upright posture and exposed to braking. Repositioned with PT (Event I, blue) vs Standard belt (Event J, red). B-post belt geometry.

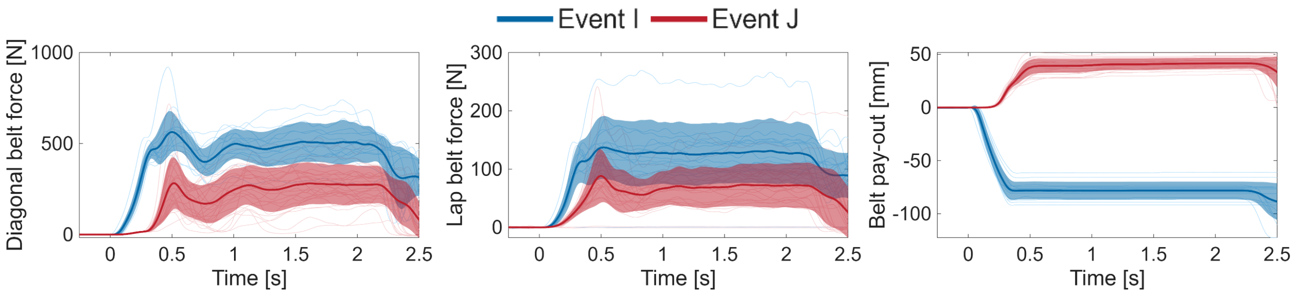


Fig. E 19. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers in upright posture and exposed to braking. Repositioned by PT (Event I, blue) vs Standard belt (Event J, red). B-post belt geometry.

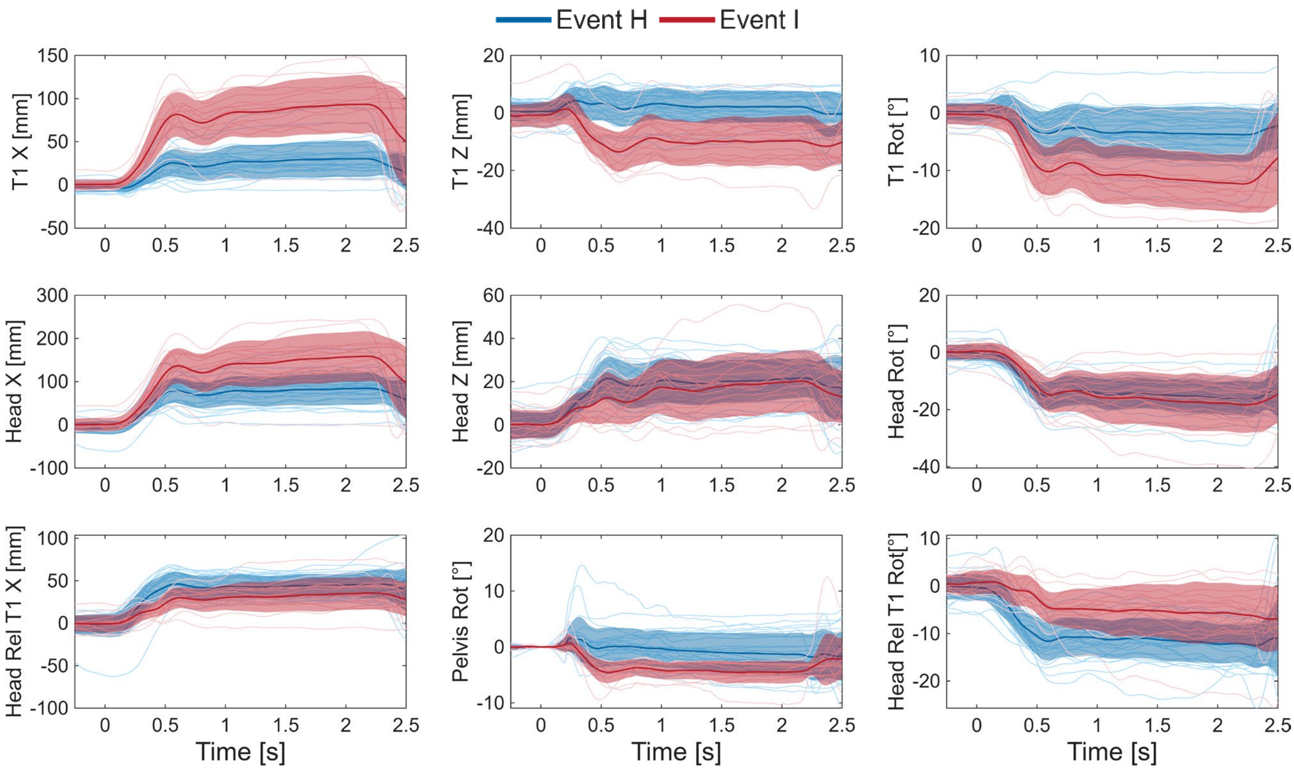


Fig. E 20. Displacements for volunteers in upright posture repositioned by PT belts and exposed to braking. BIS belt geometry (Event H, blue) vs B-post geometry (Event I, red).

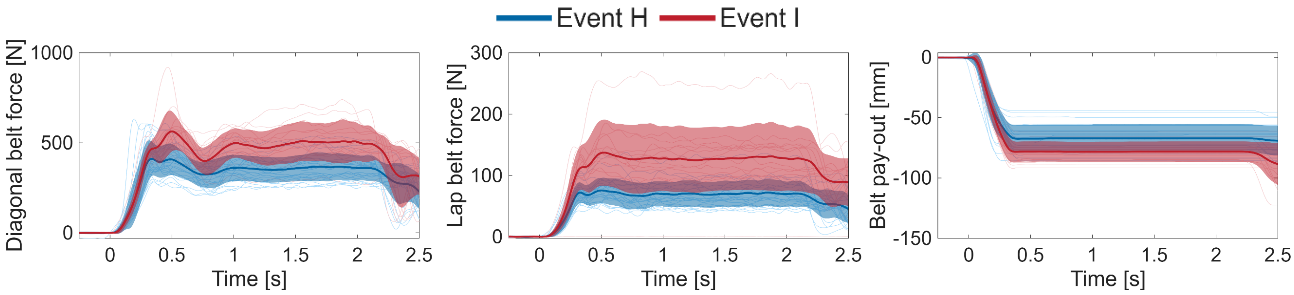


Fig. E 21. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers in upright posture repositioned by PT belts and exposed to braking. BIS belt geometry (Event H, blue) vs B-post geometry (Event I, red).

Appendix E7 - What is the repositioned occupant posture compared to an upright occupant, and what if no repositioning occurs?

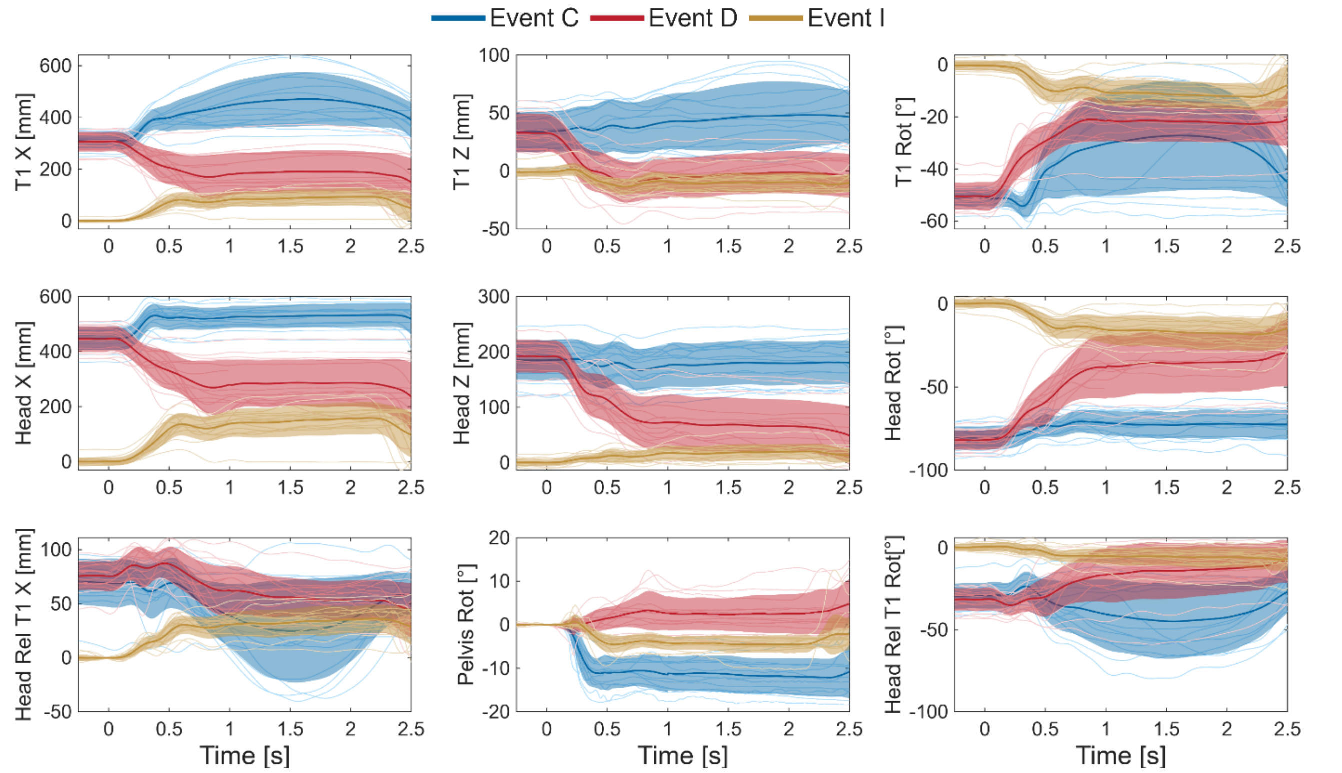


Fig. E 22. Displacements of volunteers exposed to braking. Forward-leaning posture when restrained by a standard belt (Event C, red) vs Forward-leaning posture when repositioned by PT belt (Event D, blue) vs Upright posture when repositioned by PT belt (Event I, yellow). B-post belt geometry.

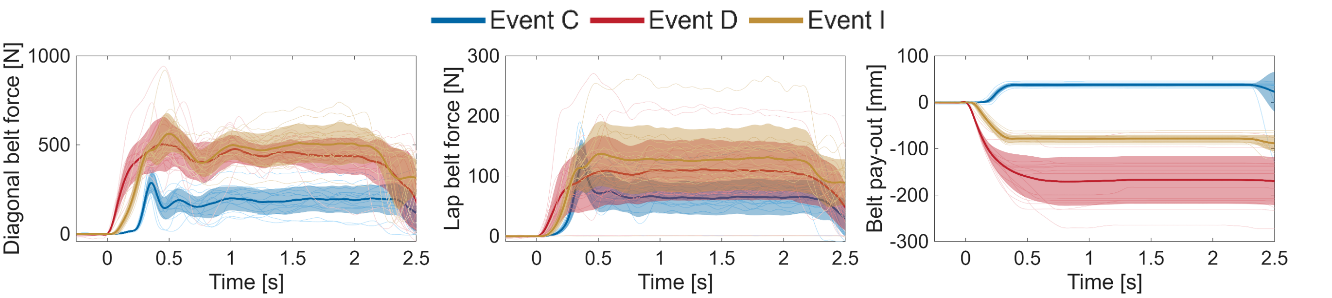


Fig. E 23. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers exposed to braking. Forward-leaning posture when restrained by a standard belt (Event C, red) vs Forward-leaning posture when repositioned by PT belt (Event D, blue) vs Upright posture when repositioned by PT belt (Event I, yellow). B-post belt geometry.

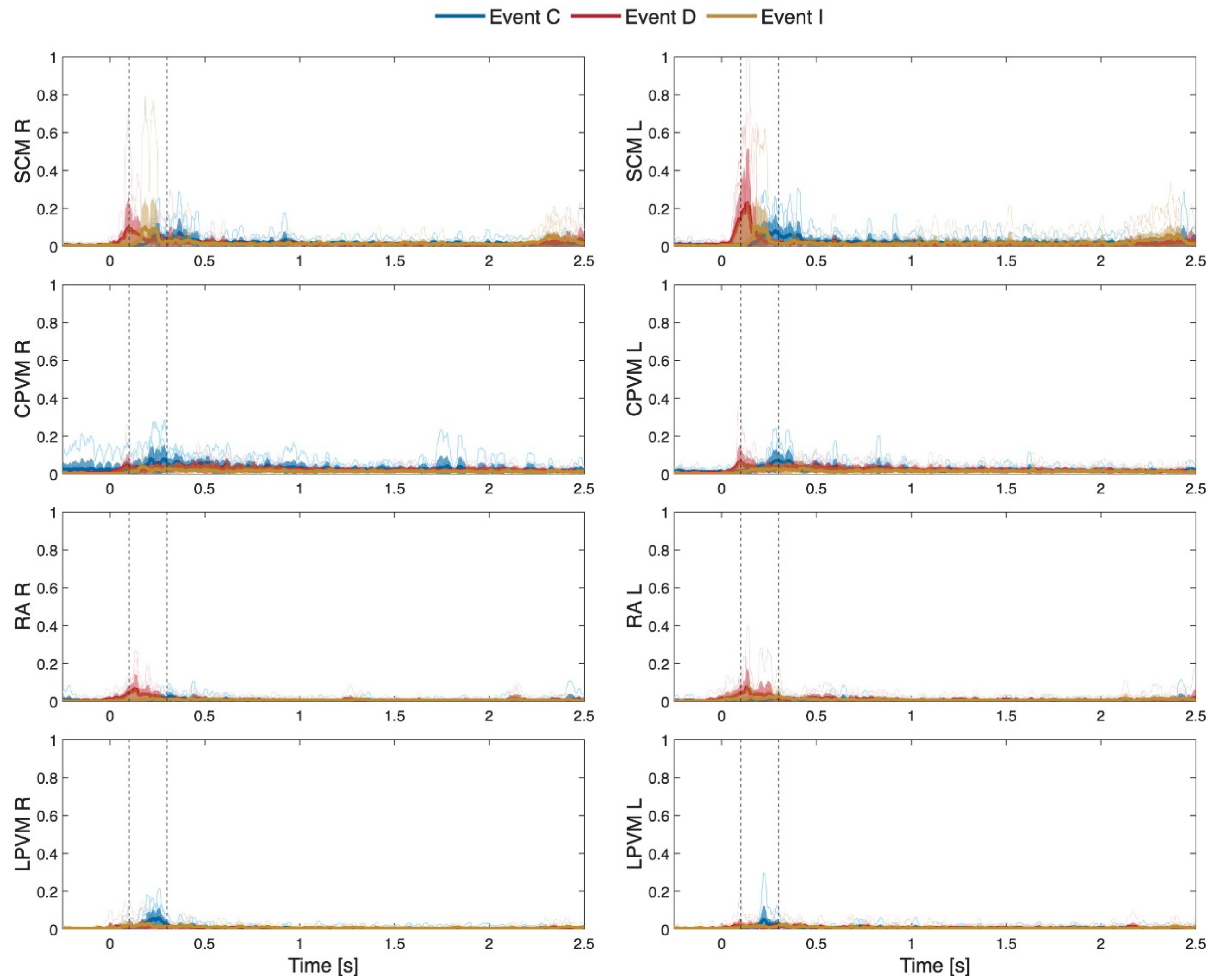


Fig. E 24. EMG for volunteers exposed to braking. Forward-leaning posture when restrained by a standard belt (Event C, red) vs Forward-leaning posture when repositioned by PT belt (Event D, blue) vs Upright posture when repositioned by PT belt (Event I, yellow). B-post belt geometry.

Appendix E8 - Do occupants respond differently to braking depending on their initial posture?

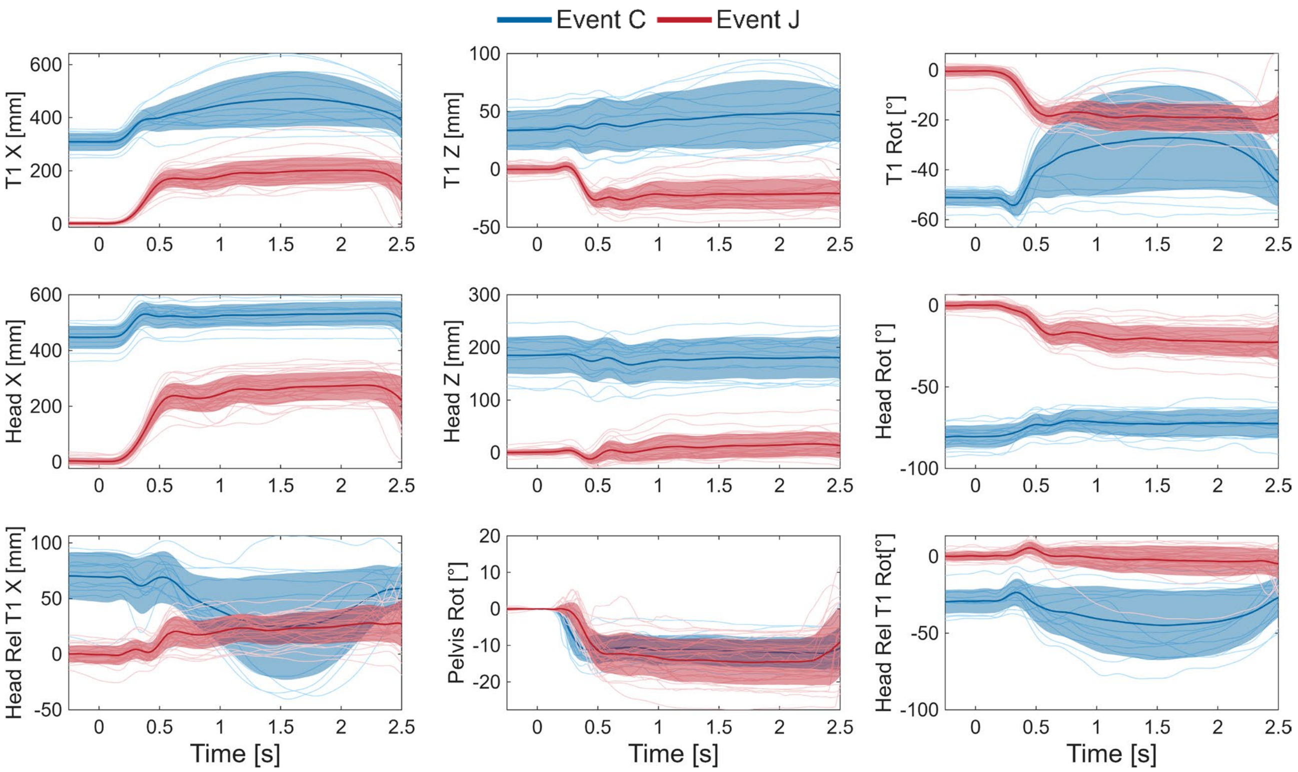


Fig. E 25. Displacements for volunteers exposed to braking while restrained by a standard belt in B-post geometry. Forward-leaning (Event C, red) vs Upright posture (Event J, blue).

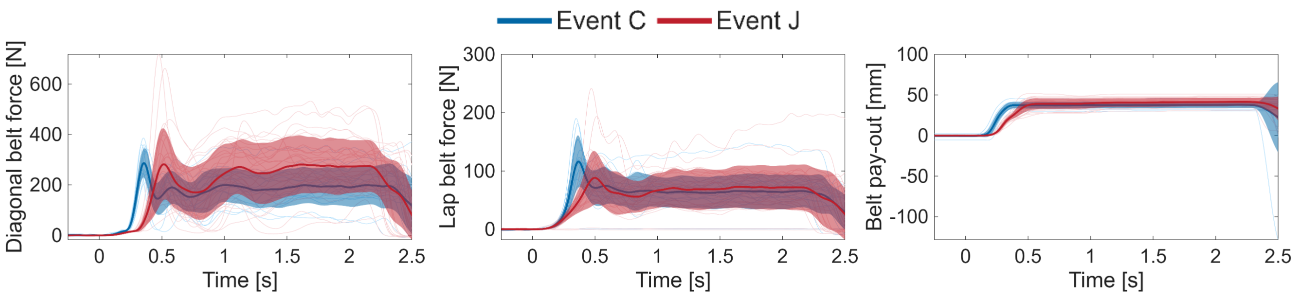


Fig. E 26. Diagonal and lap belt forces and pay-out (negative=pay-in) for volunteers exposed to braking while restrained by a standard belt in B-post geometry. Forward-leaning (Event C, red) vs Upright posture (Event J, blue)

XIII. Appendix F – Comparing Events - statistical analysis of data

Table F 1 provide p-values from an ANOVA analysis comparing kinematics between different events. Table F 2 provide p-values from an ANOVA analysis comparing EMG signals between different events. Table F 3 provide p-values from an ANOVA analysis comparing belt data between different events.

TABLE F 1.
COMPARING KINEMATIC DATA ACROSS DIFFERENT EVENTS USING ANOVA. UNDERLINED P-VALUES ARE BELOW SIGNIFICANCE THRESHOLD

Event	T1 X	T1 Z	T1 Rot	Head X	Head Z	Head Rot	Head Rel T1 Rot	Pelvis Rot
B vs D	0.00	0.57	0.00	0.00	0.13	0.07	0.68	0.00
B vs E	0.01	0.34	0.21	0.01	0.09	0.33	0.86	0.00
E vs F	0.37	0.47	0.17	0.44	0.48	0.65	0.63	0.03
F vs G	0.04	0.12	0.06	0.10	0.33	0.41	0.77	0.29
H vs I	0.00	0.00	0.00	0.00	0.04	0.33	0.00	0.00
I vs J	0.00	0.00	0.00	0.00	0.01	0.39	0.00	0.00

TABLE F 2.
COMPARING MUSCLE DATA ACROSS DIFFERENT EVENTS USING ANOVA. UNDERLINED P-VALUES ARE BELOW SIGNIFICANCE THRESHOLD

Event	SCM_R	SCM_L	CPVM_R	CPVM_L	RA_R	RA_L	LPVM_R	LPVM_L
B vs D	0.95	0.21	0.65	0.84	0.59	0.88	0.64	0.98
B vs E	0.33	0.14	0.12	0.17	0.13	0.12	0.81	0.76
E vs F	0.92	0.65	0.97	0.78	0.70	0.41	0.86	0.31
F vs G	0.01	0.01	0.18	0.12	0.08	0.09	0.81	0.19
H vs I	0.63	0.33	0.69	0.43	0.53	0.57	0.26	0.48
I vs J	0.59	0.20	0.07	0.13	0.79	0.17	0.22	0.02

TABLE F 3.
COMPARING BELT ACROSS DIFFERENT EVENTS USING ANOVA. UNDERLINED P-VALUES ARE BELOW SIGNIFICANCE THRESHOLD

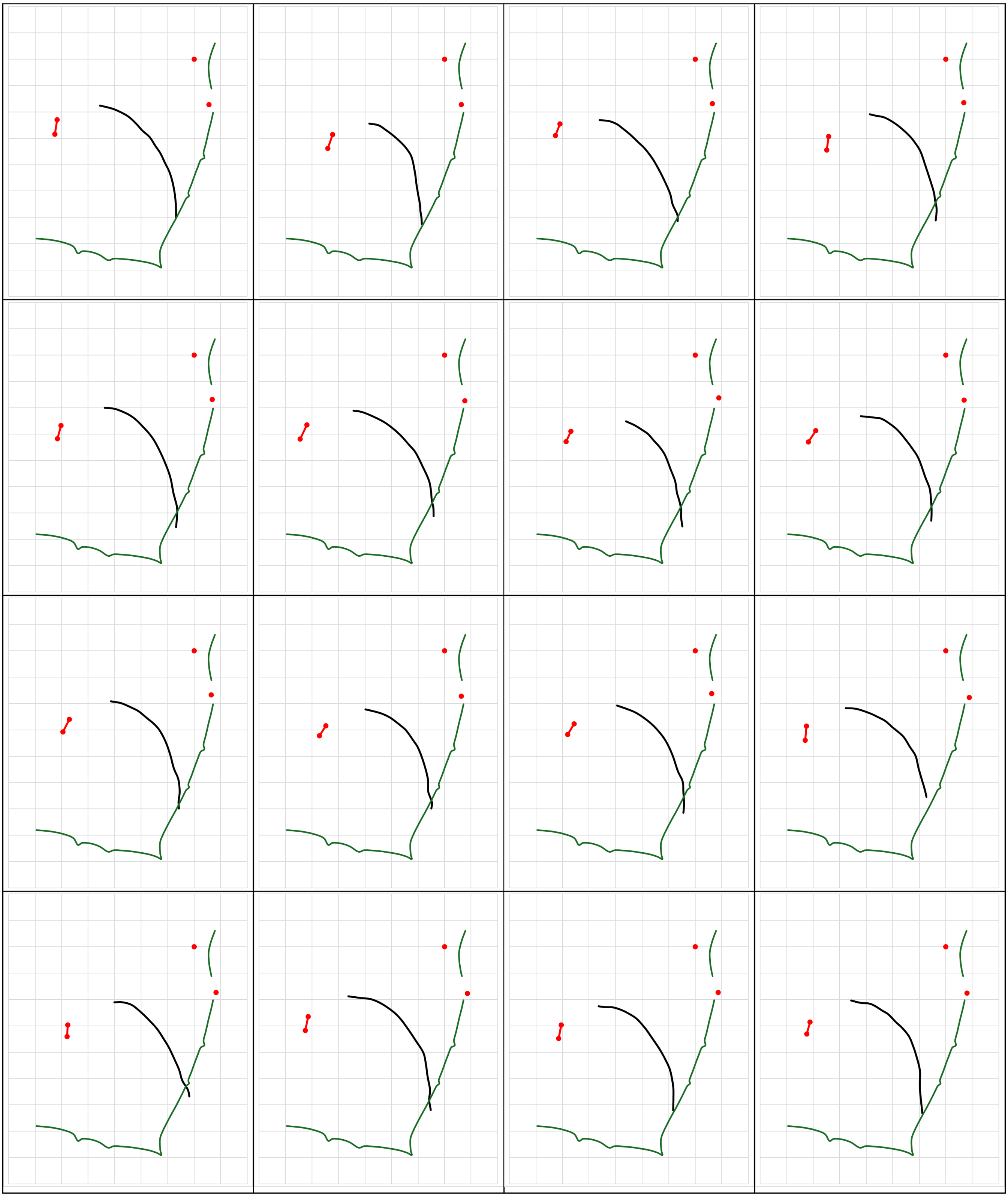
Event	Diagonal belt	Lab belt	Belt pay-in
B vs D	0.00	0.04	0.03
B vs E	0.08	0.00	0.00
E vs F	0.01	0.00	0.00
F vs G	0.00	0.00	0.01
H vs I	0.00	0.00	0.10
I vs J	0.00	0.00	0.00

XIV. Appendix G – Volunteer back contour in initial forward-leaning posture

Table G 1 provides schematic representations of the initial posture during forward leaning immediately prior to the initiation of an event (Event 13). The rearmost torso contours were obtained by digitizing the outline of the volunteer from the C7 vertebra to the lumbar region, as captured in side-view camera images. Note that, for the lumbar region, the depicted contour line does not represent the midsagittal plane position.

TABLE G 1

TORSO CONTOUR IN BLACK. THE FRANKFORT PLANE IS INDICATED BY RED LINES (UPPER MOST REFERENCE POINT LOCATED AT THE AUDITORY CANAL). UNDEFORMED MIDPLANE SEAT SURFACES IN GREEN. MID BELT AT B-POST AND BIS D-RING LOCATIONS PRESNTED WITH RED DOTS. GRID SPACING 100 X 100 MM.



XV. Appendix H – Pretest diagonal belt angles

Table H 1 provide angular orientation of the belt-to-shoulder contact position relative the D-ring position for each volunteer when leaning-forward just before the start of Event 13 and Event 16. The belt angle was measured in side view camera images and presents the angle in the vehicle coordinate system relative to the horizontal plane. Since the D-rings were above the belt to shoulder contact points for all volunteers the values were negative.

TABLE H 1
ANGULAR ORIENTATION OF THE D-RING TO SHOULDER BELT SEGMENTS.

Volunteer	Initial BIS belt angle (deg)	Initial B-post belt angl e
1	-7.4	-36.5
2	-17.4	-40.3
3	-11.7	-42.8
4	-12.0	-47.4
5	-8.1	-42.7
6	-7.7	-41.8
7	-15.4	-47.7
8	-10.0	-42.0
9	-12.3	-44.8
10	-14.7	-48.0
11	-9.5	-44.2
12	-13.7	-39.1
13	-10.3	-41.7
14	-1.2	-38.7
15	-13.5	-41.5
16	-3.3	-38.9